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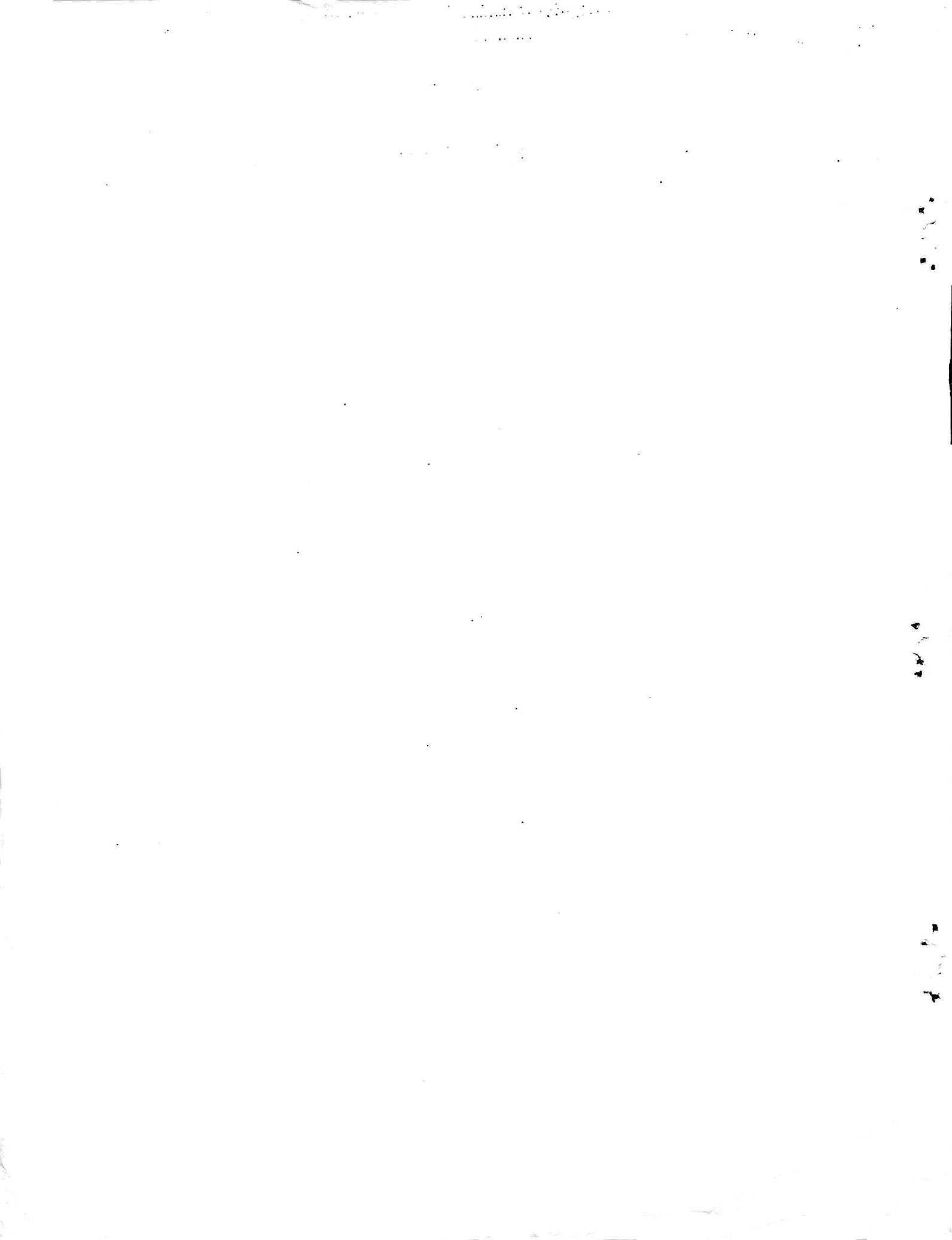
ROBOTICS TECHNOLOGY: AN ASSESSMENT AND FORECAST

Aerospace Industrial Modernization Office
Wright-Patterson Air Force Base, OH

Jul 84

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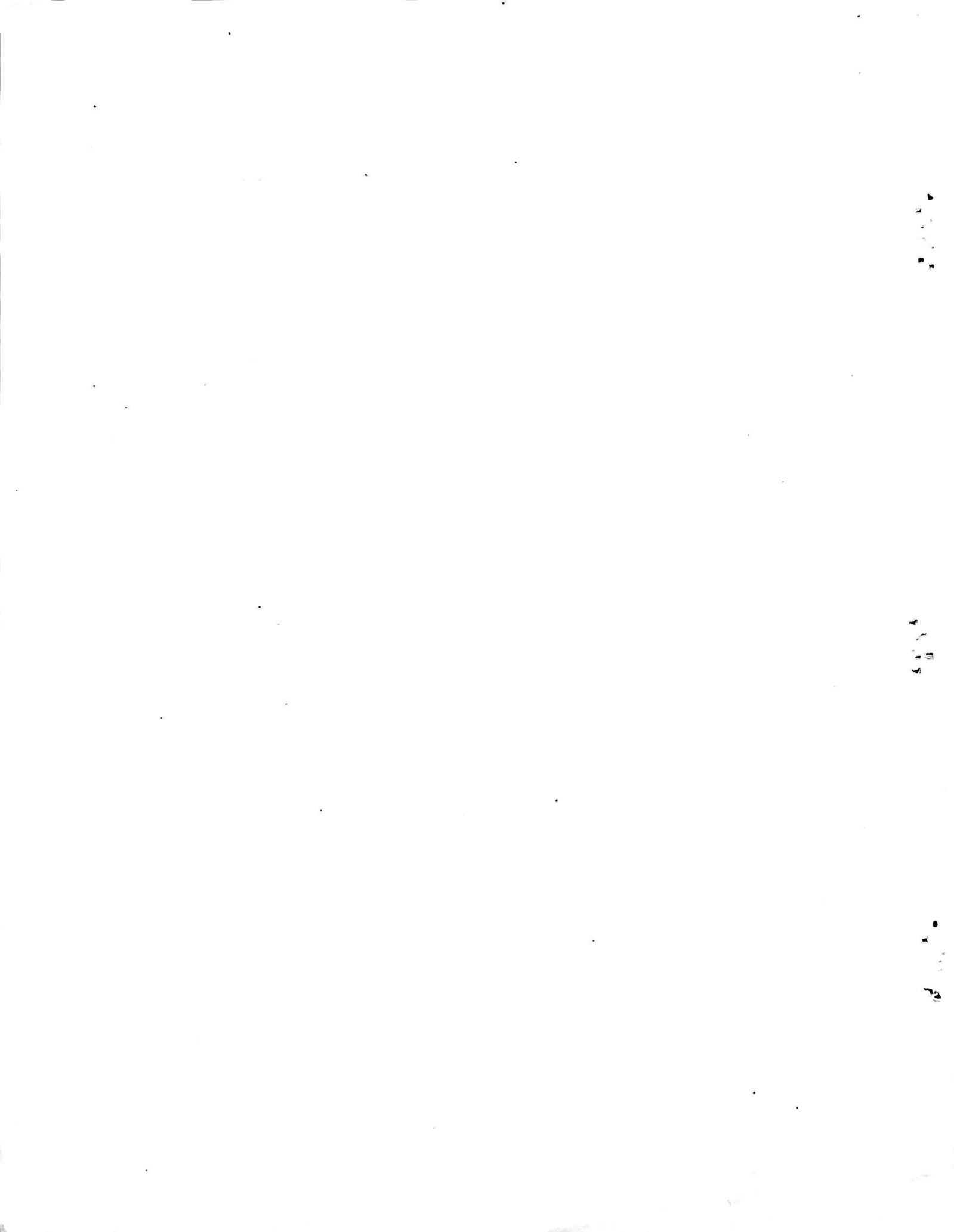
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PREFACE

This study was performed by DHR, Incorporated under contract (No. F33615-83-D-5083, Delivery Order 0001) to the Aerospace Industrial Modernization Office of the Air Force Systems Command. The Project manager for this effort at the AIM office was Mr. Fredrick C. Brooks.

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EXECUTIVE SUMMARY

Robotics will be a major driving force of the defense industrial base as industrial robots grow and mature into an integral part of next generation computer-integrated manufacturing processes. In this context, the Aerospace Industrial Modernization (AIM) Office of the Air Force Systems Command has been tasked to evaluate robotics technology as a means of improving the manufacturing technology base of the aerospace industry. Consequently, the AIM Office has recently initiated a technology assessment of robotics, of which the results are presented in the present report. The major objectives of this study are to:

- o Perform a critical assessment of the current status of the technology;
- o Review key world-wide R&D activities and discern the principal thrusts and trends in robotics R&D; and
- o Perform a technological forecast addressing future functional capabilities, emerging application areas and future directions of robotics producers and end-users.

CURRENT TECHNOLOGY

Current Functional Capabilities

The functional elements of a generic robot can be grouped into three categories: mechanical, sensing and control. In addition, the performance of a robot can also be judged on two additional dimensions: internal integration of constituent components and external integration with the surrounding environment. Internal integration is normally evaluated by a number of system performance characteristics such as accuracy, repeatability, resolution, reach, working configuration, speed and load capacity. External integration is measured in terms of robot's performance within a work cell or a flexible manufacturing system.

In the following, the current functional capabilities of a generic robot are described by specifying their technical limitations presently encountered in practice:

Mechanical

- o Manipulators, in general, are still clumsy and slow with massive components.
- o Actuators are of three types: pneumatic, hydraulic and electric. Pneumatic actuators are difficult to control while hydraulic actuators are frequently subject to disruption due to failure of precision mechanical components. The major deficiencies of conventional electric actuators consist

of low power-to-weight ratio, backlash and lack of rigidity under load due to the use of reduction gearing. In general, no currently available actuators can incorporate control capabilities to modify actuator responses.

- o End-effectors, in general, are crude with no sensor or just binary tactile sensors. They do not have the desired interchangeability in the absence of standardization, and have to be custom-designed for specific applications.
- o Locomotion exists in the form of rail, gantry or wheeled systems and is typically limited to structured environments.

Sensing

- o Vision sensing is limited by poor resolution and difficulty in depth mapping. It is too slow for real-time processing and is hindered by lack of standardization.
- o Tactile sensing capabilities exist in binary form or simple force/torque sensing. Current tactile sensors are not very robust and have a narrow dynamic range.
- o Proximity sensors employ IR, ultrasonic or laser sources. IR and ultrasonic sensors are characterized by poor range resolution and inaccurate location; while laser sensors are furthest developed but expensive to implement.

Control

- o Current controllers can best be characterized as primitive computers.
- o Control software primarily exists at walk-through or teach-pendant levels with some limited off-line programming and crude sensory integration capabilities.
- o Robots generally operate as an "island of automation" and interact with their surroundings via part feeders or fixturings.

Established and Emerging Robotic Applications

A further measure of current robot's capabilities is the degree to which industrial robots have penetrated various application areas. Examination of the application areas penetrated by robots as well as those likely to emerge in the near future helps to identify the present status of robotics technology. Following is a tabulation of robotic applications, separated into established and emerging areas.

Established Applications:

- o Spot welding
- o One-pass, non adaptive arc welding
- o Two-pass arc welding with limited adaptive path control
- o Two-pass arc welding with limited adaptive process control
- o Material handling with parts in known location and orientation or transferred from known areas
- o Easy-mating assembly
- o Editable coating/painting with single or multiple robots
- o Inspection of coarse features
- o Sealant application with bead flaw detection
- o Routing or drilling with template
- o Coarse grinding with simple force or torque sensing
- o Investment casting
- o Die casting with simple inspection
- o Forging
- o Plastic injection molding

Emerging Applications:

- o Arc Welding aided by expert systems
- o Material handling with part recognition and acquisition for transfer from unstructured supply, e.g. bin picking
- o Fast close-fitting assembly with active compensation
- o Painting/coating with inspection and adaptive process control
- o Routing or drilling without template
- o High-precision grinding

Industrial Usage of Robots

Robots have penetrated several industries to different extents. The automotive industry is the largest user of industrial robots in the U.S., acquiring approximately 50 percent of the total number of installed robots. Other industries that have also made significant use of robots include foundry, electronics, aerospace, non-metal light manufacturing, and heavy-equipment manufacturing. Below is a listing of robotic applications that have established at least a moderate presence in these industries.

- o Automotive: Spot welding, material handling, painting, die casting, arc welding, inspection, assembly and sealant application.
- o Foundry: Material handling, investment casting, die casting, forging and finishing.
- o Electronics: Material handling, assembly, inspection, arc welding, sealant application and plastic molding.
- o Aerospace: Painting/Coating, material handling, inspection, finishing, sealant application and investment casting.
- o Non-metal light manufacturing: Plastic molding, material handling, sealant application and assembly.
- o Heavy-equipment manufacturing: Arc welding, material handling, painting/coating and finishing.

Recent Developments in Robotics Industry

The dynamic, high-tech robotics industry has undergone remarkable changes in the last decade. Since its inception, the industry has evolved through three major stages:

- o Industry definition in the late 1960's and most of the 1970's,
- o Strong initial growth in the 1979-81 period, and
- o Industry consolidation from 1982 to the present.

At the peak of its high-growth period, the robotics industry was characterized by an annual growth rate of about 90% and a large influx of new companies. Many of these companies were financed by venture capital attracted by the industry's high growth potential. This initial growth, however, was relatively short-lived as end-users began to realize the limited capabilities of available industrial robots. In this period the

industry was dominated by fewer than six robot producers.

Since 1982, robot sales have slowed considerably. The U.S.-based robot market is becoming highly competitive as a large number of robot vendors (over sixty) vie for a limited market, which is still growing but at a much slower rate, about 30% per year. This leads to a strong belief in the robotics community that an eventual shake-out of the industry is imminent, if indeed it has not already begun. In this environment, the robotics industry is undergoing structural changes which are evident in the following observations:

- o The market-share hierarchy of robot producers has begun to change substantially to reflect the momentum gained by several new start-ups and giant corporations. The current top six robot producers, on the basis of their market shares, are GMF Robotics, Cincinnati Milacron, Automatix, Westinghouse, ASEA and DeVilbiss.
- o Companies are starting to seek out niches by applications, price ranges, targeted customer bases and levels of robot sophistication.

R&D ACTIVITIES

Air Force

Agencies active in the Air Force robotics technology base include the Air Force Office of Scientific Research (AFOSR), the Air Force Systems Command (AFSC) and the Air Force Logistics Command (AFLC). The following table summarizes the key R&D performers and topics sponsored by these Air Force agencies.

AGENCY/PROGRAM	KEY PERFORMERS	R&D TOPICS
AFOSR	<ul style="list-style-type: none">o University of Michigano SRI Internationalo Stanford University	<ul style="list-style-type: none">o High Performance manipulatorso Sensory controlo Microcomputer controllero Manufacturing cells

AFSC MANSCIENCE	<ul style="list-style-type: none"> o Martin Marietta (Subcontractors: ERIM, McDonnell Douglas, RPI, Stanford Univ., University of Mass./ Amherst, VPI) o Honeywell (Subcontractors: Adept Technology, Stanford University, SRI) 	<ul style="list-style-type: none"> o Hardware and software design for automated assembly o Development of multi-arm systems for assembly and inspection
AFSC MANTECH	<ul style="list-style-type: none"> o McDonnell Douglas o RVSI o Grumman Aircraft o Fairchild Aircraft 	<ul style="list-style-type: none"> o Machine control language (MCL) o Vision sensing o Drilling/riveting o Drilling/trimming
AFLC	<ul style="list-style-type: none"> " General Electric o Georgia Tech 	<ul style="list-style-type: none"> o Packaging and Warehousing o Inspection of turbine blades

Other Federal Agencies

In addition to the Air Force, significant robotics R&D is also supported by other federal agencies, which include the Navy, the Army, DARPA, NASA, and NSF. Below is a summary of major thrusts of these programs:

Navy:

- o Office of Naval Research (ONR) supports about a dozen university programs to perform basic research on sensory control and advanced sensing techniques.
- o Major projects sponsored by NAVSEA and NAVAIR include autonomous mobility for navigation, welding for ship hull fabrication and riveting in airplane refurbishing.

Army:

- o The Army supports a cohesive, directed R&D program to address the question of how applicable will robotics and artificial intelligence be to battlefield situations.
- o Other efforts supported by various Army commands are focused on improving manufacturing technologies. Areas of emphasis are assembly and inspection. Current commitments in terms of on-going FY84 projects and planned FY85 projects amount to approximately \$3.1 million for manufacturing technology.

DARPA:

- o DARPA's robotics efforts are designed to support the three services in high-risk, high-payoff projects. Its long-term goal is to establish a technology base for non-manufacturing military applications in maintenance logistics and weapons support.
- o R&D projects sponsored by DARPA are concentrated in two areas: control of specialized manipulators and integration of advanced sensory input for manipulator control and navigation.

NSF:

- o NSF supports a broad range of basic research projects covering all aspects of robotics.
- o Total funding for FY83 was about \$4.8 million, of which \$2.4 million was devoted to sensing, \$0.9 million to control, \$1.0 million to manipulation, and \$0.5 million to system performance.

NASA:

- o NASA commits about \$1.5 million in FY84.
- o NASA - sponsored projects were focused mainly on vision processing, supervisory control, man-machine interaction and system integration.

Foreign R&D

The U.S. faces a strong technological challenge in robotics from three groups of developed countries, Japan, Western Europe and the Soviet Bloc. In general, technological advances achieved in most of these countries are highly competitive, although the U.S. is still in the forefront in the development of robotics technology. The key features of robotics R&D in these countries are summarized as follows.

Japan:

- o Robotics R&D in Japan is established as a national policy, which targets those R&D efforts in support of early commercialization and removal of humans from hazardous environments.
- o This strategy is implemented by two national R&D programs. The first program is aimed at improving those robotic capabilities required for nuclear, undersea and rescue applications. The second national program, also known as the Jupiter Project, is focused on those problems identified as the key technological barriers to robotic commercialization.
- o The first program was initiated in 1982 with a commitment of about \$130 million for the next seven years. The Jupiter Project began in 1983 with an estimated funding in the range of \$55-80 million in its entire duration.

Western Europe:

- o Countries with a concerted, well-supported R&D program in robotics include the United Kingdom, France and West Germany. Also significant, but of a smaller magnitude, are programs in Sweden, Norway and Italy.
- o Robotics R&D in the U.K. is characterized by close cooperation between government and industry. Funding emphasis is, therefore, placed on immediate payback projects targeted to industrial problems. A major program, which funds most university R&D in robotics, was created in 1980 through the Science and Engineering Research Council and jointly funded by Government and industry.
- o Robotics R&D in France is mainly represented by a national three-year, \$350 million program, starting in 1983. This program is concentrated on R&D in manufacturing technology and also includes training of robotics specialists and promotion of robotic implementation.
- o At the center of robotics R&D in West Germany are efforts performed at various Fraunhofer Gesellschaft Institutes. Their funding resources are equally contributed from government block grants, industry and specific government contracts. In general, their R&D activities are mainly driven by specific applications.
- o Other significant robotics R&D programs in Western Europe exist, at a smaller scale, in Sweden, Norway and Italy. Most do not have a cohesive national focus and are normally

Most do not have a cohesive national focus and are normally led by major robot producers such as ASEA of Sweden, Trallfa of Norway and Olivetti of Italy.

Soviet Bloc:

- o Among the countries belonging to the Soviet Bloc, with the exception of Yugoslavia, robotics R&D is well coordinated through the Council for Economic Mutual Assistance (CEMA).
- o CEMA members are approximately a decade behind the West in robotics technology mainly due to their deficiencies in computer and electronics technologies.
- o Notable features of their robotics R&D are advances made in manipulative and sensing technologies and a strong drive to achieve standardization and modularity.

Summary of R&D Activities

Sources	Highlights
U. S. Federal:	
o Air Force	o AFOSR committing about \$2-3 million for basic research. Multi-year, multi-million dollar commitments to develop robotics technology base provided by AF MANTECH and MANSCIENCE programs.
o Navy	o Basic research supported by ONR and technology development in autonomous mobility, ship hull welding and aircraft de-riveting sponsored by NAVSEA and NAVAIR.
o Army	o Committing about \$3 million in FY84 and FY85 mainly to improve manufacturing technologies in assembly and inspection.
o DARPA	o Supporting the three services in high-risk, high-payoff projects.
o NSF	o Sponsoring basic research, totaling about \$4.8 million in FY83.
o NASA	o Committing about \$1.5 million in FY84 with a strong emphasis on control and integration issues.

Foreign:

- o Japan
 - o Represented by national programs: a seven year, \$130 million program that targets nuclear, undersea, and rescue applications and the multi-year Jupiter project that commits \$55-80 million to speed robotics commercialization.
- o Western Europe
 - o West Germany, France and the United Kingdom have concerted, well-supported programs. Other significant programs also exist in Italy, Sweden and Norway.
- o Soviet Bloc
 - o Robotics R&D coordinated through CEMA. Robotics development is lagging the Western countries in general, but make significant progress in manipulation, sensing, modularity and standardization.

TECHNOLOGICAL FORECAST

The present study is concluded with a technological forecast, which consists of four parts: projected capabilities, application forecast, industry trends and technological trends.

Projected Capabilities

Mechanical

Manipulator:

Future manipulators will require greater speed, more versatility and enhanced accuracy. In the near term, these needs are being addressed in the development of rigid but lightweight manipulator structures, improved joint and bearing design, parallel linkages and antagonistic drives. In the long term, light, flexible robot arms will become common.

Actuator:

Current actuators suffer from inefficiency, lack of stiffness under load and backlash. In the near future, direct drive electric actuators will alleviate many of these shortcomings. In a longer time frame, tendon drives with high power transmission capabilities will be able to replace conventional actuators for some of the arm joints.

End Effector:

End effectors in use today are generally bulky and lack versatility. The next generation of end effectors will have quick change capability for versatility and will incorporate local sensing. The long term solution to most end effector shortcomings will be the development of a general-purpose dexterous hand, with high resolution force sensing "skin".

Mobility:

Mobile robots in the near term will be descendants of today's computer-controlled parts-transfer carts as used in automated factories. They will run on wheeled suspensions, and improved mechanical registration techniques will allow precise positioning of the robot at work stations. In the long term, mobile robots will make use of active tracked suspensions, legged locomotion and crawling/climbing abilities.

Control

Current work in distributed processing, networking and development of hierarchical software will result in substantially more sophisticated controllers in the near future. Sensing systems will acquire dedicated satellite processors, supplying the controller with sensing results instead of raw data, while software operating systems will manage the housekeeping of distributed processing. The controller will utilize more complex dynamic models to produce better accommodation of workload effects. In the longer term, controllers will tie into local area networks to communicate with surrounding machinery and to receive programs and commands from higher-level supervisory computers. As vertical integration improves, the robot controller will lose much of its identity, becoming just another link in the processing hierarchy.

Sensing

Vision:

The two primary developmental needs for robotic vision are lower cost and increased speed in processing. The near term results of current R&D will be VLSI processors for 2D and 2 1/2D vision that are fast enough to provide real-time results, usable for adaptive control. In the long term, processing speed will be sufficient for real-time results from 3D vision, while signal processing methodologies will be applied to allow use of vision in uncontrolled, visually noisy environments.

Tactile:

In the near future, the VLSI technology that will help vision systems will also enhance tactile sensing. Tactile arrays of modest size and resolution will be packaged with their own dedicated processors, while force/torque sensing will become common. Tactile sensing sophistication will continue to improve, and in the long term will result in high resolution force sensing tactile arrays, capable of acquiring 3D shapes by touching.

Proximity/Ranging:

In the near term, developments in this type of sensing will be driven by application needs, such as eddy current sensing of rivets for aircraft refurbishing and ultrasonic sensing to aid robots in acquiring parts. In the longer term, proximity sensing will become more important due to the needs of mobile robots as an essential component in obstacle avoidance and navigation.

Sonic:

The majority of interest in robotic hearing is focused on speech recognition for command purposes. Today and in the near future, this capability is very limited with respect to vocabulary and reliability. Speech recognition will become a significant capability for robots in the long term with the appearance of artificial intelligence and natural language capability.

Integration

Short Term:

- o Internal integration will improve as some level of communication standardization becomes accepted; sensing systems will be the first well-modularized components.
- o External integration will reduce the robot's dependence on expensive and inflexible fixturings and feeders, replacing them with simpler mechanical systems. Coordination with external computer systems for task assessment and off-line programming with simulation testing will become common for sophisticated installations.

Long Term:

- o Internal integration will become much better, with industry-wide standards for interconnection; a buyer will be able to add to his robot's capabilities by plugging in modules.
- o External integration will connect and coordinate entire production lines, including many robots. CAD/CAM systems will connect with graphics-aided robot programming systems, which will then download the resulting programs to the robot production line. This supervisory system will perform the necessary planning, stock and machine allocation, maintain inventory and maintenance schedules, and support a sophisticated Management Information System.

Application Forecast

With respect to the effect of future developments in robotics, there are three major categories of robotics applications:

Low Growth Applications - Developments in robotic technology will not produce sweeping increases in robotic penetration.

- o Spot Welding
- o Spray Painting and Coating
- o Forging
- o Investment Casting
- o Sealant/Adhesive Application
- o Die Casting

High Growth Applications - As improvements in the laboratory and development stage become commercially available in the near term, these applications will show very rapid increases in robotics penetration.

- o Material Handling
- o Arc Welding
- o Routing, Drilling, Grinding
- o Inspection
- o Assembly

Blue Sky Applications - These applications require capabilities that are still in early developmental stages. Robotic penetration will be very slow starting, and will not become significant in the near term future.

- o Housekeeping
- o Construction Labor
- o Maintenance by Expert Systems
- o Hazardous Environment Rescue
- o Orbital Construction

Industry Trends

At present, the number of companies in the U.S. producing and marketing robots or robot components is quite high, more than today's market can support. A shake-out is occurring, and many of these companies are likely to withdraw from the market. Small companies that would like to enter the market with a line of components, such as vision systems, are severely hampered by the lack of industry-wide standardization.

During the next several years, the robotics industry is likely to be rather frenetic, characterized by new companies entering the field, some existing companies withdrawing, and corporate take-overs. However, some trends seem likely to appear:

- o Many larger firms will market flexible manufacturing systems

- o Suppliers of complete turnkey systems will become more prominent, minimizing the hidden costs of a robot.
- o Greater product differentiation and market segmentation will develop, as vendors carve out specific markets.

Technological Trends

The developing trends of robotics technology are:

- o Separation of high sophistication robots from simple robots will be established.
- o Sensing will become both faster and better, and integration of sensory information will be much more efficient.
- o Mobility will be easily available due to improved mechanical and navigation systems.
- o Future robots will take advantage of lighter materials and more efficient design.
- o Perhaps the greatest change will be in the extent of robot integration. Sophisticated robots will communicate downward to dedicated satellite processors, sideways to adjacent robots, and upward to supervisory control systems.
- o Lower cost is going to be a major trend in both sophisticated and simple robots due to improved technology and economies of scale.
- o Hybrid robotic/teleoperated devices will become common, leading the way in applications that will eventually be handled by fully autonomous robots.

1. Introduction

Decrease in industrial productivity has been an issue of national concern for the last several years. This concern has permeated the entire U.S. industry and, without exception, strongly affected the aerospace sector. As a consequence, the defense industrial base is faced with a threatening erosion that could entail a significant reduction of the nation's defense capacity. The Aerospace Industrial Modernization (AIM) Office of the Air Force Systems Command has recently been tasked to assess and improve the manufacturing technology base of the aerospace industry. As a part of this effort, the AIM office has initiated an assessment of U.S. and foreign activities associated with robotic technology. This assessment will support the establishment of a full-spectrum, long-range plan for the Air Force robotics implementation program. This plan is intended to guide and accelerate the implementation of robotics technology into the aerospace community in order to reduce the cost of manufacturing, maintaining, repairing and servicing aerospace systems. This report represents the results of the above-mentioned assessment of the current and projected status of U.S. and foreign robotic technology.

Because robotic technology is still at a formative stage, it is necessary in assessing the current technology to establish some working definitions and concepts. The lack of established industrial practices that will be shown to permeate the industry includes even basic definitions. For the purposes of this report, then, the Robot Institute of America definition of a robot as a "reprogrammable multi-functional manipulator" will be adhered to. As a result, the present study will be focused on robots as such and thus will not address in detail related technical and economic issues such as integrated work cells and Flexible Manufacturing Systems (FMS).

Additionally, there are several concepts used in this report that should be clarified here. The first is the concept of "state-of-practice". By state-of-practice we generally mean the level of technology currently in manufacturing use. Clarification of this term will be provided where necessary for each specific example. Secondly, the concept of near and far term is used throughout the discussion of the technological forecast. By near term it is meant to imply a range of several years, generally about two to five years. Similarly, far term is intended to indicate the five to ten year range. The following discussion is devoted to the organization of the report.

The main body of this study begins in Chapter Two with a detailed view of current robotics technology. This presentation is divided into four sections: the robotics industry, current robotic capabilities, current robotic applications, and industrial usage of robots. Each of these topics is discussed separately to highlight the difference between what robots can do today and what they are doing today. Generally the technological capabilities exceed the state-of-practice by at least several years. Additionally, it is realized that the degree of industrial usage of robots and even the structure of the robotics industry play an important role in determining the kinds of products and technology that are and will

soon become available. From this multi-sided approach to describing the current robotic technology, an understanding of the driving forces behind technological developments can be developed. This information is used later in the report to draw some conclusions about future robot usage.

Chapter Three summarizes a world-wide study of robotics research and development programs, divided into U.S. and foreign activities. Both the U.S. activities and the foreign activities will be classified, when possible, according to the R&D funding community and the R&D performing community. This distinction is made to draw attention to the individual government-sponsored R&D projects and overall funding strategies. Based on an analysis of these project goals and directions, the thrusts of robotics research are determined in each of the most active research communities, both domestic and abroad. These individual thrusts are then synthesized into an overall picture of world-wide robotics research and development.

The fourth chapter of this report consists of a methodical forecast of robotic technology. The adopted approach includes a study of the anticipated advances from in-progress research programs. Specifically, the forecast begins with a list of projected functional capabilities, mainly on the basis of the preceding analysis of research topics, goals and directions. The forecast continues with a summary of projected robot usage by application, based on the conclusions drawn in Chapter Two combined with the projected functional capabilities. It is believed that this forecast approach, combined with in-depth consultations with a well-represented expert panel provides a sound, practical prediction of future robotic technology. The concluding section of this forecast chapter, Future Directions, is devoted to a synthesis of the above projections into a concise, directed forecast of both technological and industry trends.

While the body of this report presents a complete picture of robotic technology, there are some additional discussions that might enhance the reader's understanding of several of the topics presented. These discussions are elaborated at length in the appendices. Appendix A includes a systematic analysis of key considerations in current robotic manufacturing applications. An in-depth study of industrial and academic R&D programs is presented in Appendices B and C, respectively. Finally the references and personal contacts made during the course of this study are listed in Appendices D and E.

2. Current Robotic Technology

In this chapter, the current status of robotic technology is reviewed and assessed from several perspectives. In Appendix A, all current robot applications are reviewed in detail. There, in each application area, the involved manufacturing process, basic elements of a typical robot used in such applications, economic motivations and technological constraints in robot usage, and specific examples of the considered application area are reviewed and assessed. In the following, the information contained in Appendix A is highlighted, and at the same time the current technology is assessed from a more general point of view. A quick update of the robotics industry is first provided to inform the reader about the major features of the industry and the latest developments in the field. Section 2.2 then examines a generic version of an industrial robot as it is being used and analyzes its functional capabilities systematically, going through the major components of a robot's subsystems. In Section 2.3, robotic applications are again reviewed with emphasis placed on an overall analysis of robotic applications, economic motivations and technological barriers hindering robot penetration. Section 2.4 is then devoted to assessment of present usage of robots in various industries with regard to industrial operations and response to robot applications. Finally, a composite picture of the present technology is summarized in the last section of this chapter. It is believed that this approach to technology assessment will present a comprehensive understanding of current robotic technology which is balanced and most useful from the perspective of various industrial sectors associated with robotics.

2.1. U.S. Robotics Industry - An Update

The U. S. robotics industry has demonstrated the vitality and dynamism that are typical of a rapidly growing high-technology sector. Sales and production have been expanding at a vigorous annual rate of 30-60% from the 1970's through the early 1980's. As in most high-growth areas, the industry has evolved through several stages: industry definition in most of the 1970's, strong initial growth in the 1979 - 1981 period, and industry consolidation from 1982 to the present.

From the start, the growth pattern of the robotics industry was influenced by two major factors: first, the hourly cost of direct labor was lower than the hourly cost of operating an industrial robot; and second, the benefits expected from a new, unproven technology were still uncertain. As a result, by 1970, ten years after their introduction, only about 200 industrial robots were in use throughout the U. S.

During the 1970's, however, the U. S. economic environment changed significantly. Manufacturing productivity declined steadily and labor cost increased while robot cost did not rise excessively. These trends were taking place at the time that robots became more sophisticated in both manipulative and control/ sensing capabilities. Usage of robots in manufacturing began to increase significantly in the 1970's. Robot population increased from about 200 in 1970 to about 1700 in 1978. This

characterized the formative stage of the robotics industry, during which a sizable industry was taking shape from early developmental efforts. In this period, the basic technology solidified and a core group of robot manufacturers established well-defined product lines.

In the next three years, 1979 - 1981, the robotics industry underwent a major development characterized by high growth in sales and considerable penetration into new application areas. This was spurred by the rapidly increasing labor cost coupled with the reassurance of successful applications of robots in automotive and foundry industries. Known for their widespread use in this period were robots designed for spray painting, spot welding, parts transfer and machine loading. Robot population increased at a remarkable rate from about 1700 in 1978 to about 4500 in 1981. This period also witnessed the influential role of venture capital in raising the number of robot producers from under a dozen in 1978 to about 80 by the end of 1981.

Most recently, in the last two years, 1982 and 1983, the robotics industry entered a period of consolidation, which was characterized by a slowdown in growth and entrance into the robotics industry of several powerful giant companies. The initial enthusiasm appeared to have leveled off and end-users began to recognize the limitations as well as capabilities of robots. At the same time, continued infusion of new capital into the industry further increased the number of robot manufacturers and component suppliers. These trends are indicative of an industry that is still growing vigorously but has become highly competitive. This has led to a strong belief in the robotics community that an eventual shake-out of the industry is quite imminent, if indeed it has not already begun.

Presently, there are more than 60 U.S.-based robot manufacturers with indications that this number is still rising. They generally fall into one of the following three categories:

(i) Pioneer robot producers that either started in robotics like Unimation, or entered early from their lead in the machine tool area, such as Cincinnati Milacron and Prab Robots;

(ii) New start-ups financed by venture capital attracted to the field by its high growth potential, including among many others, Automatix and Advanced Robotics; and

(iii) Major corporations (e.g. General Electric, IBM, and Westinghouse) seeking to parlay their related strengths into robotics and to support their interests in factory automation through robotic developments.

As a result, the early robotics industry was heavily dominated by a small group of pioneer companies. Their strong market positions, however, have slowly been eroded as new companies enter the market. With the industry so dynamic and at such a young stage, it is not surprising to see that relative market shares have undergone great flux in the last decade. A closer look at the market shares of five producers with the largest sales in 1980 (i.e. Unimation, Cincinnati Milacron, Prab Robots, DeVilbiss and ASEA) reveals that their dominance has slipped considerably, from a combined percentage share of 90.9% in 1980 to 42.2% in 1984. This is illustrated in Figure 2-1 below.

	<u>1980</u>	<u>1981</u>	<u>1982</u>	<u>1983</u>	<u>1984</u>
Westinghouse/ Unimation	44.3%	44.0%	32.9%	15.1%	9.2%
Cincinnati Milacron	32.2%	32.3%	16.7%	17.1%	14.1%
Prab Robots	6.1%	5.3%	6.5%	5.0%	4.9%
DeVilbiss	5.5%	4.2%	12.4%	9.1%	7.0%
ASEA	2.5%	5.8%	5.0%	5.4%	7.0%
TOTAL	90.9%	91.6%	73.5%	51.7%	42.2%

Source: Prudential-Bache

Figure 2-1: Combined Market Share of Five Selected Companies
(1980 - 1984)

In their place, there emerged two major producers, GMF Robotics and Automatix, with several others such as IBM, GE and Cybotech beginning to show their strength in the robot market. In general, the market share held by the long-standing vendors in the industry is declining, giving way to new entrants supported by venture capital and major corporations. Within this highly competitive environment, the robotics market is undergoing structural changes to the effect that:

(1) The hierarchy of robot producers in terms of their market position has begun to change substantially to reflect the momentum gained by several new start-ups and giant corporations; and

(2) Companies are seeking out niches by application, level of technological sophistication, price range and targeted customer base.

As a whole, the robotics industry is still characterized by a fairly vigorous growth despite this increasing competitiveness. This is apparent when one examines the sales trends in the last decade of this sector. Figure 2-2 illustrates the total sales achieved by the robotics industry since 1975 and the associated growth rate for each year. In the initial growth phase, annual growth rate is fluctuating about an unusually high percentage of 60% during the 1975 - 1981 period. More recently, this remarkable growth has slowed down somewhat, varying in the 20%-40% range in the 1982 - 1984 period. On the basis of the growth rate of 32%, which is an average over the last three years, it is estimated that sales will reach about \$470 million in 1985 and about \$1880 million in 1990.

In summary, a detailed breakdown of robot sales by U.S.-based vendors in the last five years is presented in Figure 2-3, where annual sales figures of the top ten U.S.-based robot producers are tabulated with their percentage market share included in parentheses.

U.S. - BASED ROBOT SALES								
YEAR	75	76	77	78	79	80	81	82
SALES (\$ MILLIONS)	8	15	26	40	60	90	155	190
GROWTH RATE (%)	87	73	54	50	50	72	23	32
								42

SOURCES: PRUDENTIAL-BACHE, FROST & SULLIVAN, NORTH & DONAHUE

P = PRELIMINARY

E = ESTIMATED

Figure 2-2: Sales by U.S. Based Vendors

SALES IN \$MILLION AND MARKET SHARE (IN PERCENT) OF U.S. - BASED VENDORS: 1980 - 1984

	1980	1981	1982	1983 (P)	1984 (E)
Unimation	40.0 (44.3)	Unimation	68.0 (44.0)	Unimation	63.0 (32.9)
Cincinnati Milacron	29.0 (32.2)	Cincinnati Milacron	50.0 (32.3)	Cincinnati Milacron	32.0 (16.7)
Prab Robots	5.5 (6.1)	ASEA	9.0 (5.8)	DeVilbiss	23.7 (12.4)
DeVilbiss	5.0 (5.5)	Prab Robots	8.2 (5.3)	Prab Robots	12.5 (6.5)
ASEA	2.5 (2.8)	DeVilbiss	6.5 (4.2)	ASEA	9.5 (5.0)
Advanced Robotics	1.7 (1.9)	Automatix	3.0 (1.9)	Cybotech	9.0 (4.7)
Copperweld	1.5 (1.7)	Nordson	2.0 (1.3)	Automatix	8.1 (4.2)
Nordson	0.8 (0.9)	Copperweld	1.5 (1.0)	Advanced Robotics	6.6 (3.4)
Mobot	0.8 (0.9)	Thermwood	1.0 (0.6)	Nordson	4.5 (2.4)
Automatix	0.4 (0.4)	Advanced Robotics	0.8 (0.5)	IBM	4.5 (2.4)
Others	3.0 (3.3)	Others	4.6 (3.0)	Others	18.0 (9.4)
TOTAL	90.0 (100.0)	TOTAL	155.0 (100.0)	TOTAL	190.0 (100.0)
				TOTAL	248.5 (100.0)
				TOTAL	355.0 (100.0)

SOURCE: Prudential-Bach Securities

P = Preliminary

E = Estimated

Figure 2-3: Sales and Market Shares of U.S. Based Vendors

2.2 Current Capabilities of a Generic Robot

This section introduces the reader to the components of a generic industrial robot, discusses the interactions of these components (internal integration), and finally considers the interaction of the robot with its surroundings (external integration) as it leads to coordination of work cells and flexible manufacturing systems. The components are described in terms of current state-of-practice; for the sake of clarity, component variations that are rarely used in production may be omitted.

The basic components of a generic state-of-practice industrial robot fall into three major groups:

1) Mechanical - These are the parts that move or produce motion. This group consists of the manipulator, the actuators that power the joints and the end effector that holds the workpiece or tool.

2) Sensing - These are the components that provide the robot with information about its environment. The main types of sensing components in use today are vision systems, tactile or contact systems and proximity systems.

3) Control - These are the components of the controller. Controllers in use today can be as simple as rotating cams that open and close air or hydraulic valves, or can be as complex as a sophisticated computer system. In the latter case, the major components and features can include the processor, I/O and interface units, mass storage, programming language or programming method, and a library of pre-written routines to perform path control and sensory integration. Figure 2-4 presents a taxonomy that illustrates the basic components of a robot. The last unit in that taxonomy, labeled system performance, represents the result of integrating the robot components (internal integration) and characterizing the way in which they perform as a whole.

Mechanical

When one first looks at an industrial robot, the component that dominates the image is the manipulator, the structural framework on which the robot is built. It is composed of rigid links connected by joints. Manipulators can be characterized by types of joints, either rotary or translational, and by the way that they are linked. The two types of joints are illustrated in Figure 2-5. Most manipulators have three degrees of freedom, i.e., three movable joints, with additional joints incorporated in the wrist between the manipulator and the end effector to increase agility. A manipulator that uses only translational joints is referred to as a Cartesian robot because the position of the wrist is specified by the position of each joint along the standard cartesian x, y, and z axes. A schematic drawing of a three joint cartesian manipulator is shown in Figure 2-6. A manipulator that combines one rotational and two translational joints is referred to as a cylindrical coordinate robot, as is illustrated in Figure 2-7. Two perpendicular rotational joints and one translational joint, illustrated in Figure 2-8, results in a spherical

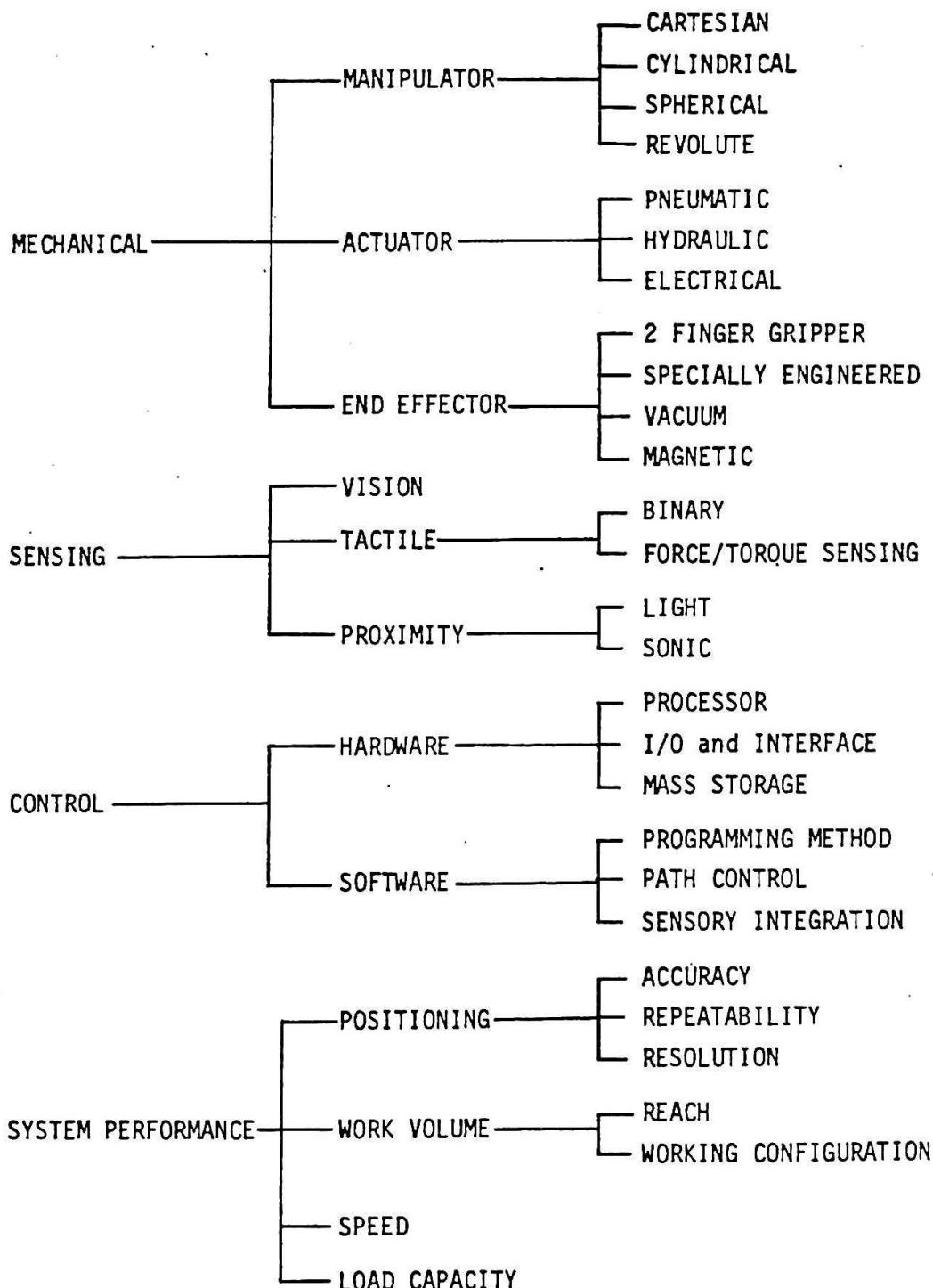
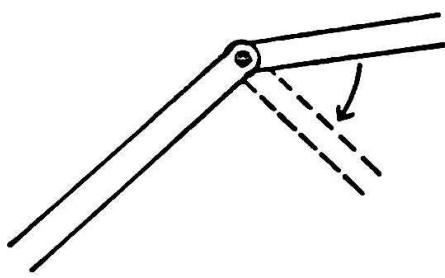
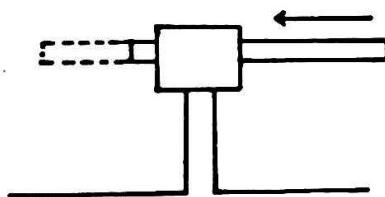


Figure 2-4: Taxonomy of a Generic Industrial Robot



ROTARY JOINT



TRANSLATIONAL JOINT

Figure 2-5: Manipulator Joints

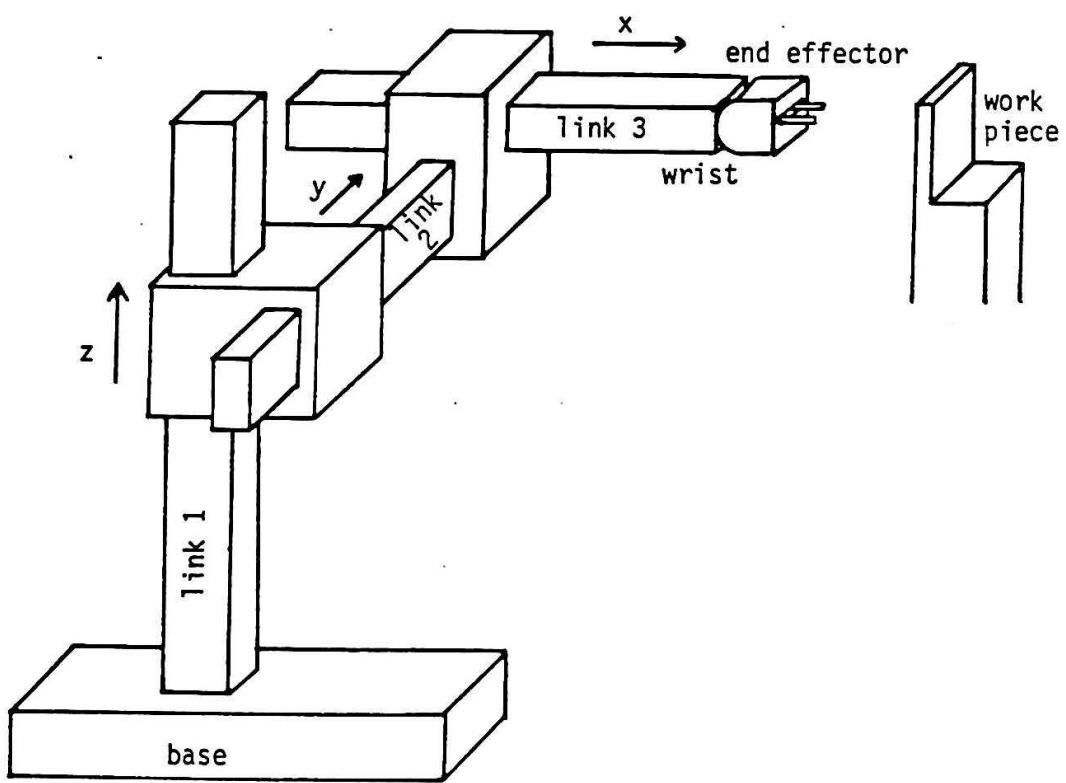


Figure 2-6: Cartesian Coordinate Robot

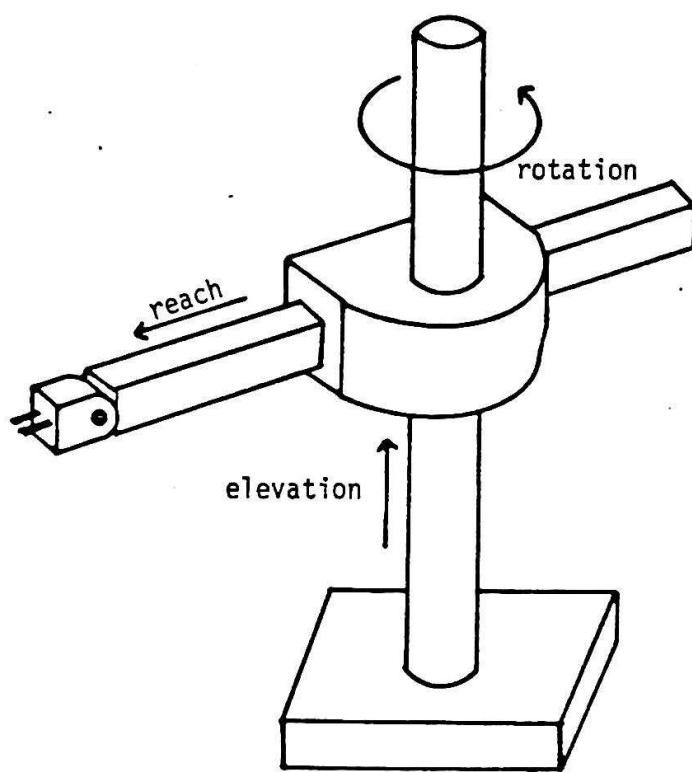


Figure 2-7: Cylindrical Coordinate Robot

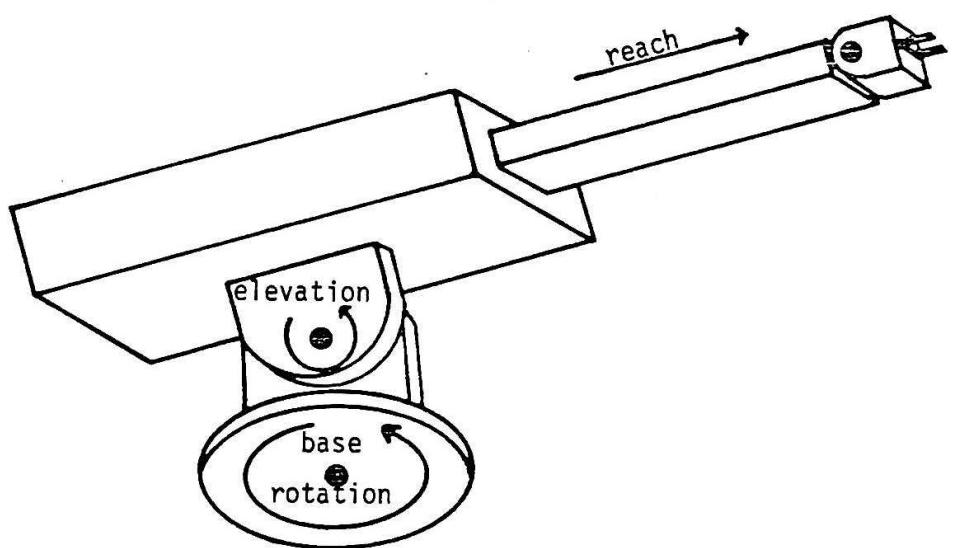


Figure 2-8: Spherical Coordinate Robot

coordinate robot. A more agile manipulator configuration consists of three rotational joints, two of them coplanar, as illustrated in Figure 2-9. This is referred to as a revolute or jointed arm; joint 1 is commonly referred to as the shoulder and joint 2 as the elbow by analogy to the human arm.

The actuators generate the force required to operate the joints of the manipulator. Three major types of actuators are in common use today: pneumatic, hydraulic and electric. Pneumatic actuators generally rely on pressurized air to move pistons that produce linear motion or rotational motion via lever arms. Hydraulic actuators draw their energy from high pressure hydraulic fluid, and can be linear actuators or rotary motors, which produce rotation without requiring lever arm linkages. Electric actuators are high performance electric motors that generally produce rotary motion through reduction gearing to provide adequate torque (though direct drive electric motors that eliminate the need for gearing are now appearing) and linear motion by means of ball screw types of converters. End effectors are attached to the end of the manipulator (frequently through a wrist that provides additional degrees of freedom to improve dexterity). They are the components that actually hold the tool or grip the workpiece. Tool-type end effectors in common use today are spot welding guns, welding torches and spray guns. End effectors that grip the workpiece are usually specially designed by the robot user for a particular application. Grippers in use today typically consist of two fingers moving towards each other while the fingers remain parallel. However, gripping of unusually shaped objects with this simple motion has also been demonstrated by re-configuring the finger geometry. Certain types of workpiece can be picked up by end effectors that use vacuum or magnetism.

Sensing

Robotic sensors commonly used today in general fall into three types: vision, tactile (touch sensing and force sensing), and proximity. Robotic vision systems use a video camera to produce an image consisting of a grid of discrete elements called pixels. Typical resolution of the image may range from 100 by 100 up to approximately 400 by 400 such elements. Each element senses the brightness at that position in an analog manner with potentially many levels (gray-scale levels). Most vision systems in use today are called binary systems because the analog output of each pixel is thresholded by external circuitry to yield a binary output, i.e., light levels above the threshold are labeled black, and below the threshold are labeled white, or vice-versa. Many processing algorithms can be applied to interpret these binary images. The major algorithms in use today rely on important geometrical features to characterize the workpiece. For this reason, present vision systems are more often used for inspection and quality control than for acting as adaptive sensors.

In binary vision systems, careful design and attention must be engineered into the accompanying lighting and optical systems to ensure the reliable acquisition of a high contrast image. For some applications, more sophisticated picture-processing algorithms are used on the original analog (gray-scale) data, enhancing contrast and extracting additional important features. A common method of reducing the complexity of the interpretation problem

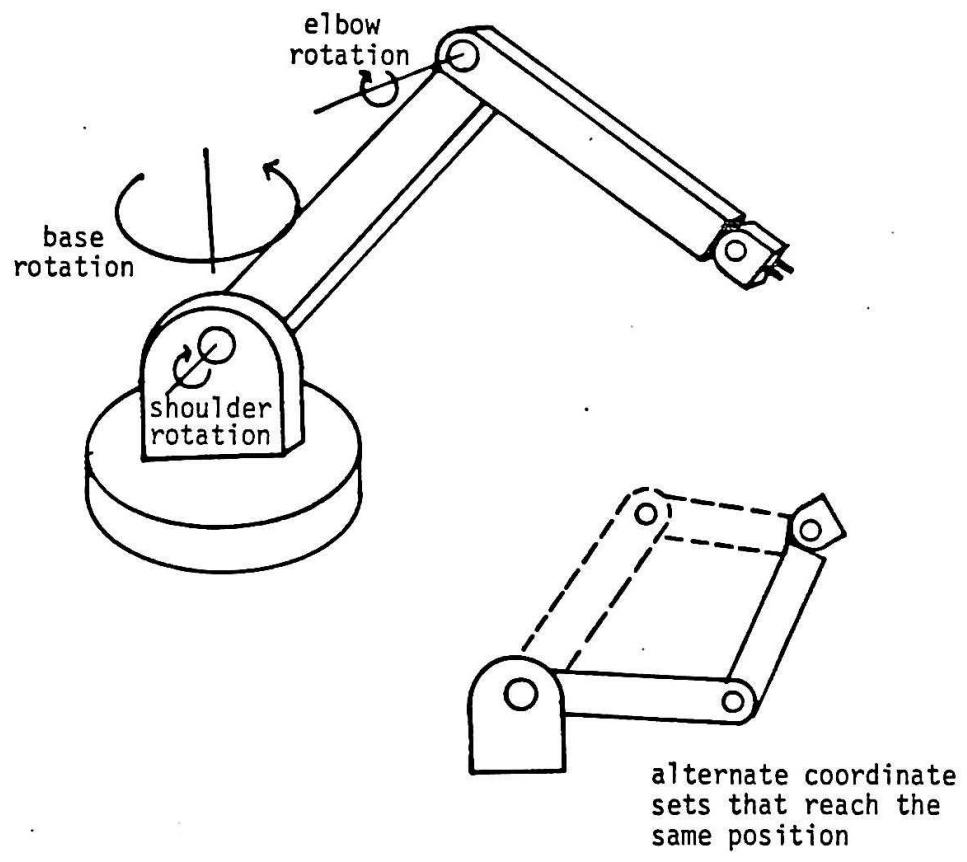


Figure 2-9: Revolute Coordinate Robot

is the use of structured light to illuminate the workpiece. An illustration of the use of structured light applied to a beveled seam to be welded is given in Figure 2-10. An overview is given in Figure 2-10a, showing the seam to be examined; Figure 2-10b shows the arrangement in side view with the camera looking straight down, and the light stripe source illuminating the seam at an angle. The image produced by the video system is shown in Figure 2-10c. The two critical measurements, location of center of seam and depth of the seam are easily and quickly extracted from this image.

Tactile or touch sensing is more common than vision sensing; at its simplest level, an ordinary micro switch located on the end effector responds to presence of an object in the gripper to verify that the robot is holding something. This is called binary contact sensing because the switch only gives a yes/no indication. Simple contact switches are also used for safety purposes: mounted along the manipulator, they can detect contact with unexpected obstacles while the arm is moving.

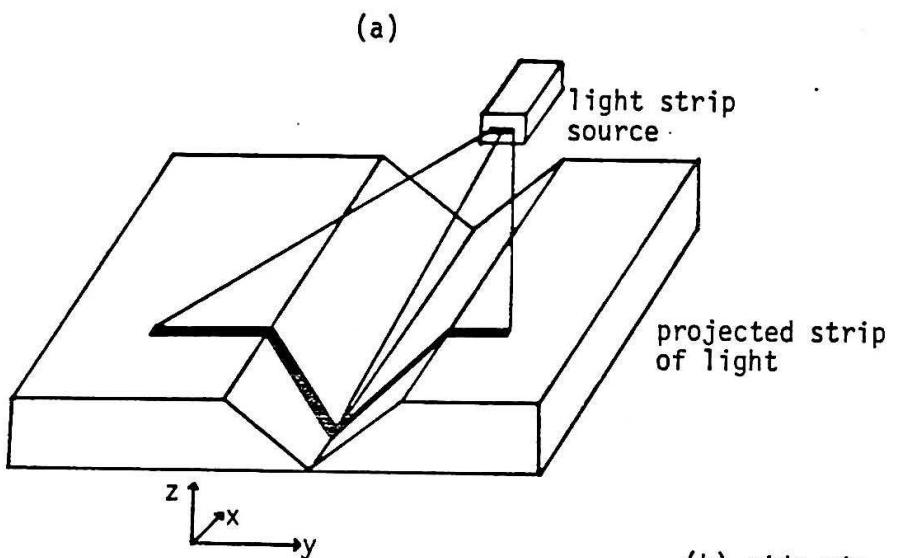
Another increasingly popular type of tactile sensing is force sensing. It is a step beyond simple contact detection, indicating not just that the robot is touching something, but also how hard it is touching. The amount of force applied can be detected with electronic strain gauges or piezoelectric transducers, which produce an electrical signal indicating how high a force is being exerted. Force sensors in use today are generally limited to sensing along only one axis.

Proximity sensing is commonly used as a substitute for simple contact sensing. For example, instead of an object in the gripper closing a contact switch, it interrupts a light beam to verify that the part is in the gripper. Because there is no physical contact, this type of sensing is not subject to wear, as are contact switches, and the light source commonly is infrared to avoid interference from ambient light.

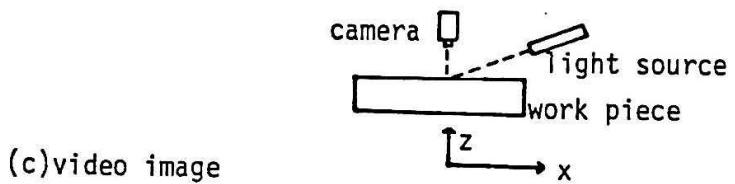
Control

In today's sophisticated industrial robots, the robot controller is essentially a small computer system. The central component is the processor, which is frequently characterized by the number of bits it uses in parallel for data manipulation. In general, the more bits that are used for the data line, the faster the processing becomes. This is why 16 bit processors are considered more desirable than 8 bit. However, this rule is not absolute; a well implemented 8 bit system can be faster than a poorly implemented 16 bit system.

The ability to interface with other components of the robot is essential in the controller. To direct the motion of the manipulator, the controller must be able to send commands to the actuators, and generally needs to receive information about the position of each joint. Additionally, sensing systems must communicate their information to the controller. The communication of information to the processor is commonly handled through direct connection to the processor's I/O port, while commands from the computer to other components generally require conversion from the low-power signal levels generated by the processor to high power control levels needed



(b) side view



(c) video image

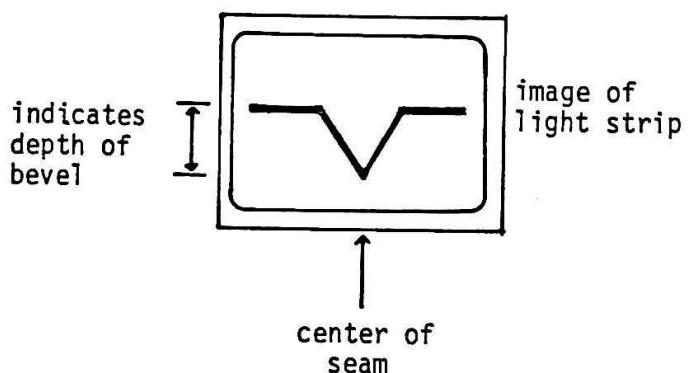


Figure 2-10: Structured Light

by other components. This conversion is commonly performed by switching transistors or electronic relays.

Some form of mass storage is usually incorporated in today's controllers. Once the robot has been taught to perform a task, a mass storage system is used to retain the commands that perform the task for later retrieval. The most common mass storage unit used in industrial robots today is magnetic tape cassettes. While less common, floppy disk systems are also used, bringing the advantages of faster access to the data and the disadvantages of higher cost and lower tolerance to harsh environments.

The controller components described so far have been, in computer terminology, hardware items. The following software items and the features they make available are equally important for a sophisticated robot.

From the point of view of the controller, there are two fundamentally different approaches to programming industrial robots: walk through or teach pendant in which the robot is "shown" what to do versus keyboard entry of the programs in which the robot is "told" what to do. For a controller to be programmed by the former method, the only software components really required are stored routines to save the joint positions "as shown", to execute the sequence of steps created by the programming and to read from or write to the mass storage device.

In contrast, a controller that is programmed by entering commands from a keyboard needs more software components. For the robot to interpret the program, it must have a compiler or interpreter that converts commands in the programming language to commands that the processor can execute. A system of this type generally requires a more extensive library of stored routines to allow commonly used command sequences to be executed quickly and easily. Normally this library will include robot oriented modules that perform tasks such as receiving information from the sensing system or systems, calculating the joint motion needed to move the end effector to a specific position command, or operating the end effector. Other modules will be program oriented, such as the language compiler, a program editor, and data storage.

Internal Integration

Work volume is simply that region around the robot which can be reached by the tool plate of the manipulator. It is determined by the mechanical constraints of the joints and the lengths of the links. It results from a combination of reach, how far from the base mounting the tool plate can extend, and the manipulator configuration. Referring back to Figure 2-6, the work volume of a cartesian manipulator is a cube whose height is the available travel along link 1, while the two horizontal dimensions are determined by the available travel along link 2 and link 3. A cylindrical coordinate robot, as illustrated in Figure 2-7, has a work volume centered on the elevation post, limited in height by the maximum elevation and extending from the center to the limit of the reach. It will be cylindrical in shape, though a wedge will be missing if the rotational joint cannot rotate a full 360 degrees. A spherical coordinate robot, as illustrated in Figure 2-8, will have a work volume that is a

subset of a sphere of a radius equal to the reach. The exclusions result from limits on the elevation axis, and limits on the base rotation axis.

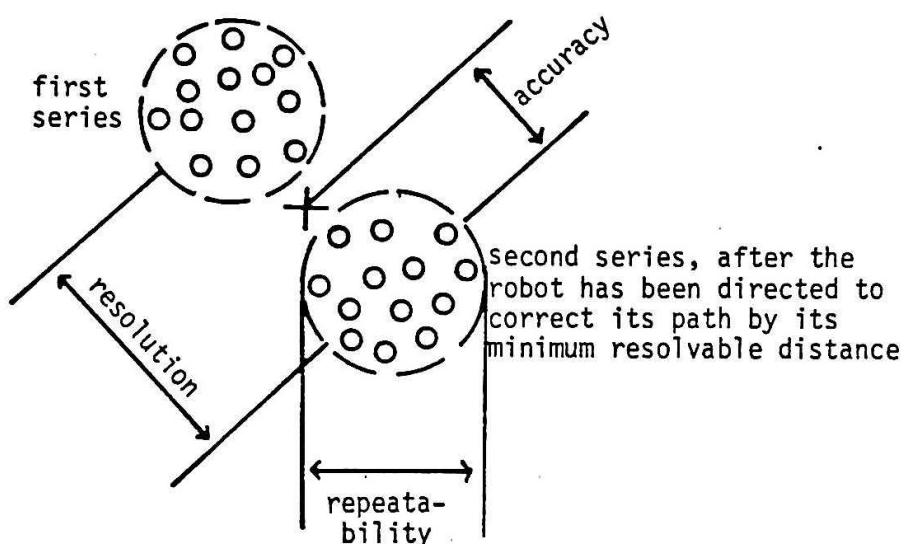
The work volume of a revolute arm is again a subset of a sphere, but the inner surface of the work volume is bounded by arcs determined by the interaction of the limits of rotation of the shoulder and elbow joints.

The concept of positioning in robotics is used to describe how well the robot is able to bring the end effector to a desired location, involving both mechanical and control aspects. There are typically three parameters that are often used to characterize positioning. "Repeatability" is the most commonly specified parameter which measures how closely the end effector can return to a position it was at previously. "Accuracy" specifies how closely the robot can position the end effector to an arbitrarily selected location. "Resolution" indicates the minimum displacement of target location that can be distinguished by the robot. Figure 2-11 illustrates these parameters. All three can be limited by the actuator's or the controller's ability to sense the joint position; it can also be limited by the software routines that perform calculations for joint position. Rotational joints tend to aggravate both of these situations. If joint position can only be controlled or sensed to a hundredth of a degree, this uncertainty is multiplied by the distance from the joint to the end effector. Furthermore, control of rotational joints involves more numeric manipulation than translational joints, making limits of computational accuracy a problem.

Sensing capability can enhance the effective repeatability and accuracy of a robot by allowing it to better define the target location. However, it cannot improve performance beyond the resolution limit of the robot. If the minimum resolution is greater than the distance to the target location, the robot will overshoot when correcting, and can oscillate between two points on either side of the target location.

Speed and load capacity at the end effector are largely determined by the mechanical components of the robot, but can be enhanced by control and sensing features. The mechanical limitations are based on how quickly the actuators can accelerate the arm plus payload and how quickly they can decelerate the load at the end of motion. The end effector can further limit these capabilities if it is unable to retain its grip through high accelerations. If the controller is capable of controlling acceleration and deceleration at the end effector, the manipulator can use maximum allowable accelerations to traverse a path in the minimum amount of time.

Load capacity also affects positioning parameters. Current robot manipulators tend to sag under load; while the joint positions may be upheld, the end effector is displaced downward. Sensing systems can detect this deviation from expected position, and modify the joint positions to accommodate for the sag, raising the load capacity while maintaining the specified positioning quality.



end effector
position on
repeated tries ○ + target point

Figure 2-11: Accuracy, Repeatability
and Resolution

External Integration

This section has, thus far, looked at an industrial robot as an individual component of the manufacturing process. While some level of interfacing and coordination with surrounding equipment is included in most robots, e.g., sensing that a die is open or that a parts feeder is empty, the goal of much of the development of industrial robotic systems is more ambitious: a true Flexible Manufacturing System (FMS). In an ideal FMS, the starting point is raw material and the end point is the finished product. The FMS should also have the capability of producing a number of different parts and performing all operations automatically. The key to a successful FMS is supervisory control, for coordinating the individual robotic work cells and managing the transportation of work pieces from one cell to the next.

The basic type of robotic cell that has been integrated into Flexible Manufacturing Systems consists of one or more CNC machine tools that are loaded and unloaded by a robot. Coordination of this cell is made possible by converting status indicators on a console to electrical signals in a communications system, and by modifying control inputs normally operated by push buttons and switches to allow electrical actuation. As a result of these conversions, the entire cell can be monitored and operated by the supervisory computer.

The movement of workpieces from one cell to another is performed by a computer-controlled handling system. The supervisory computer detects the need for parts transport (i.e., a cell has finished working on a piece), provides a cart to transport the piece, routes the cart to the next cell and orders the cell to unload the work piece from the cart. Simultaneously, the supervisor has been performing the same chores for each of the other cell-to-cell transport steps and logging all of the information on the location and status of each work piece in process.

Beyond these coordination and service tasks, the supervisory computer provides a Management Information System (MIS) that formats and can present information on the status of all work in process. Sample capabilities include scheduling projected work up to thirty days in advance, setting machining time required for each part or family of parts, and even allowing for preventative maintenance schedules on each piece of equipment. In particular, the Printing Equipment Group of Harris Corporation has a supervisory computer that optimizes scheduled production by grouping batches of parts to be produced according to part sizes, thus minimizing the number of setup changes required.

This level of integration, while not common, has been achieved with today's technology, by careful planning and intelligent use of available hardware. It represents a major thrust, not of the development of robotic technology, but of ways to make use of current robotic technology.

2.3 State-of-practice by Application

In the following section, several prevalent robotic applications

are described according to their state-of-practice. For the purpose of this section, state-of-practice is addressed with respect to the following four aspects: level of technical sophistication, degree of industrial usage, various driving forces (such as economics, productivity and safety), and technological barriers hindering further use. The set of applications chosen has been divided into two categories, fundamental applications and composite applications. The fundamental applications include welding, material handling, inspection, assembly, and painting/coating; and the composite applications are those of a less significant role.

Fundamental Applications

Welding

The technological sophistication of different robotic welding implementations varies from application to application. For most spot welding tasks, the most important characteristic of the robot function is repeatability. Smooth path control and external sensing are generally not necessary, as the robot needs only to repeatedly move to a given point, independent of the path it takes. Complicated arc welding, on the other hand, may require a much higher degree of sophistication. In general, the robot needs not only to go to a specific point or set of points, but to traverse a given path with controlled speed and acceleration if possible. In addition, it is desirable to have the capability of altering the preset path to respond to changing welding conditions. This, when possible, requires not only a high sophistication level of individual components such as sensor systems, but also a complex, integrated method of control.

Because the level of advanced technology necessary for spot welding is relatively low, robots penetrated spot welding applications early. Currently, automobile spot welding uses the largest number of robots of any manufacturing process in the U.S. In contrast, robots have not previously been as successful in penetrating arc welding applications. As the technology necessary for complex procedures has become available, however, the number of arc welding robots has risen significantly.

The driving forces for robotic implementation have been predominantly improved quality and reduced costs. While the robot is not necessarily always fast enough to justify its cost through increased throughput, the consistent quality of robotic welding is usually better than human welding. This is true both for spot welding, where fatigue due to heavy equipment and long shifts is sometimes a problem, and for arc welding, where consistency over a long weld path may lead to difficulties.

Continued and increased use of robots for spot welding is not, in general, dependent on further advances in new technology. One exception may be, however, price. As technology improves, it may not be possible to perform new functions with robotic spot welding, but it will be possible to perform established functions more economically. Increased use of robotic arc welding, though, is heavily dependent on advances in sensing and control technology. As sensing techniques improve, robotic arc welders will be able to autonomously adapt the weld path and parameters to meet varying weld conditions. This ability will reduce or eliminate the current

need for expensive, precise fixturing mechanisms.

Material Handling

The technological issues involved in current material handling applications range from the more routine to the very complex. In the simplest cases, the "pick-and-place" processes, the robot needs only to move to a prescribed location, grasp an object, move to a second prescribed location, and release the object. In the more advanced implementations, the robot may use any combination of specially engineered grippers such as magnetic or vacuum grippers, some method of smooth path control, or various sensors to locate and verify acquisition of the workpiece. The level of sophistication, then, generally depends on the specific needs of each individual implementation.

While the percentage of material handling processes performed by robots is not very high, the number of robots involved in these processes is large and, in fact, steadily rising. This is due largely to the vast number of material handling types of applications performed in industry. While not all material handling implementations are suitable for robotization, there is still significant room for robot penetration into many material handling operations, especially tool load/unload type operations.

The driving factor for robotization of material handling applications depends heavily on the work volume. If the batch size is very large, then hard automation is generally more economical than robots. Similarly, if the batch size is very small, then human labor is usually more economical than robots. There may, however, be overriding reasons for using robots in applications where they would be less economical than other methods. These reasons may include work in an unpleasant or hazardous environment, such as the foundry environment, or highly repetitive or difficult work which would cause fatigue in human laborers.

With the exception of high-precision material handling, most material handling processes can now be robotized without further technological advances, albeit some at great cost. There is a key trade-off in material handling operations, namely precise fixturing versus the ability to locate an object accurately and grasp it easily. For those applications where positioning must be very precise, it is necessary to know exactly where the workpiece is and where is the most efficient place to grasp it. This can currently be done with fixturing techniques; however fixturing reduces the flexibility of the robot and increases the system cost. As sensing technologies and gripper designs improve and become cost-effective, applications requiring great precision will use sensing devices and multi-purpose grippers rather than fixturing systems.

Inspection

Robotic inspection as a process generally uses the most technologically advanced means available. As sensor technology improves, inspection applications become more varied. Sensing systems currently used for robotic inspection include 2-D and 1ightstripe vision, as well as force sensing

and binary tactile sensing. However, other types of sensing are being implemented as advances in IR, ultrasonic, and eddy current sensing technologies have brought the price of these sensors down to a cost effective level. In addition, control technology is a key element of robotic inspection processes. To perform an inspection task, the robot needs an internal model of the ideal workpiece from which to make comparisons. In theory, this model could be as simple as a linear measurement, such as the part must be eight inches long, or as complex as a detailed 3-D model of the part. Robot controllers are becoming sufficiently sophisticated to hold, and in some cases even automatically generate, a complex internal model of the workpiece.

Until recently, sensing technology has been either unavailable or uneconomical. For this reason, robot penetration into inspection processes has been very minor. As the technologies improve and the prices drop, robotic inspection becomes more common. Additionally, because inspection processes are increasingly coupled to assembly tasks, robotic inspection will become more common with the rise of robotic assembly.

The primary reason for using robots in inspection tasks is quality control. The consistency and repeatability of the robot and the control algorithms that compare the workpiece to a model allow for not only greater, but more predictable levels of quality. Once a tolerance has been preset, the robot will reject any inferior part and accept any part that meets the tolerances, eliminating any subjectivity from the process. This consistency and predictability aid in manufacture and process planning. A Secondary reason for using robots for inspection is the capability of in-process inspection, which allows for inspection of workpieces in hazardous environments.

While the use of robots for inspection is increasing, further technological advances would speed the penetration of robotic technology into inspection processes. One of the most important factors that hold back the use of robotic inspection is not availability of new technologies but rather the need for decreasing the cost and increasing the speed of current technologies. Additionally, the areas of 3-D real time vision and precision tactile sensing arrays are very active research topics, and, when fully developed, will expand the scope of robotic inspection.

Assembly

Robotic assembly operations may be performed at a variety of sophistication levels. For easy-mating assemblies, low levels of sensor and path control sophistication are required, while for the more critical assemblies complex force sensing and vision may be necessary. In addition to advanced sensing requirements, critical path control may also be required. The geometry of assembling two closely fitted workpieces is not trivial; although a human can easily compensate for slight misalignment, a robot cannot always make the minute corrections in position and angle of attack to properly assemble two workpieces. While completely accurate and efficient assembly control methods are not yet available, partial solutions to this problem are available and are being used in production.

Because the technology necessary for close-fitting assembly has not previously been available, robots have not been used extensively in this area, and have in fact been used very little in easy-mating assembly. As the necessary technologies are improved and diffuse throughout industry, robotic assembly applications will become more prevalent.

The driving force for robotic assembly, as for robotic material handling, depends on throughput volume. For very large volumes, hard automation with fixturing systems is more economical than robotics, while for very small batches human labor can be more economical than robots. For those volumes of work where robots have the potential for being economical, robotic assembly has the advantage of increased consistency over human labor. Just as for inspection, the high repeatability of the robot affords a higher and more predictable level of quality control than human systems. A secondary incentive for using robots for assembly involves clean room and hazardous or unpleasant environments. Using a robot for an operation that must be performed in a clean room eliminates the complications of human preparation for the clean room.

The three most important technical barriers to extended use of robotics in assembly tasks are sensor technology for easier part acquisition, force feedback control, and advanced control technology for accurate assembly algorithms. Additionally, error recovery algorithms are currently not sufficiently sophisticated to do much more than simply abort an operation. Ideally, these algorithms should be able to isolate the problem and, if the problem is not critical, continue the assembly task.

Painting/Coating

In general, robotic painting and coating operations require a very low level of technological sophistication. For example, sensors are not widely used in painting applications. The most critical aspect of the robot technology necessary for painting tasks is smooth path control. In some of the more recent painting applications, however, the robot controller is called upon not only to direct the path of the robot and control the painting apparatus, but also to coordinate the painting with the movement of an assembly line and with other concurrent operations such as door opening.

Because robotic painting and coating operations require a minimum level of technology, in combination with the fact that this technology has been available for some time, robots have shown a heavy penetration into the painting industry, especially automobile paint spraying applications. In fact, several different robot manufacturers have built reputations solely on their paint spraying robots.

The majority of painting robots, as mentioned, are used by the automobile industry. Because the automobile industry deals with fairly high volumes of throughput, the robots are more cost effective than human workers in terms of increased throughput. In addition, there are several other important considerations for using robots in painting operations. One consideration is quality. If a satisfactory painting path is programmed into the robot, it will follow that path exactly, cycle after cycle, day after day. This

will result in very consistent, high quality painting. In addition, the spray painting environment is potentially very hazardous to humans. By replacing a human with a robot, the manufacturer not only removes a human from a hazardous environment but also eliminates the need for expensive ventilation systems and protective masks that are necessary when a human is performing the painting.

Work pieces or assemblies to be painted by robots still require accurate fixturing (expensive and not readily modified). The use of vision sensing would considerably enlarge the field of application for painting robots. What is required is the development of 3-D vision technology at acceptable prices.

Composite Applications

The final six robotic applications to be presented (sealing/bonding, finishing, investment casting, die casting, forging, and plastic molding), have been classified as composite applications for the following reason: while these applications have been significantly penetrated by robotics, they are technologically equivalent to one or more of the previously mentioned applications. For example, the robotic technology involved in robotized forging is similar to simple material handling, with the possible addition of a specialized end effector or sensor. For this reason, these applications will be discussed as a group, with references to those applicable technologies that have been previously described.

In general, the composite applications are characterized by an adaptation of generic robotic technology to a specific task. Thus, there is usually a moderate to high level of technological sophistication among these applications. For example, robotic sealing/bonding and investment casting are extensions of painting and material handling techniques, respectively. Added to these generic technologies in both of these applications, however, are the complex path control capabilities required for each application. Similarly, finishing operations can be accomplished with basic material handling techniques enhanced with advanced sensing capabilities such as force and torque sensing.

Each of these six applications enjoys a fair degree of robot penetration. With the exception of some of the very advanced sensing and path control capabilities, the generic technological capabilities have existed for some time. This has given the technology a chance to penetrate and be refined by each application. Die cast loading/unloading, for example, was among the very first types of robotic applications, with the first implementation appearing in the early 1960's.

Due to the varied nature of the composite applications, there may be many different factors affecting the considerations for using robotic technology. Safety and environmental factors, for example, are major considerations in using robots for forging and plastic molding applications. In contrast, increased consistency and quality of the workpiece is the primary driving force behind robotic implementation in investment casting applications. For sealing/bonding applications, the increased speed of the robot results in a higher throughput and profitability compared

to human labor.

For the most part, the composite applications are not dependent on further advances in technology to realize a greater penetration. The technology, as mentioned, is and has been generally available. The greatest barriers to further robotic implementation in these areas seem to be hesitancy on the part of end-users, not a deficit in technology.

2.4 Robotic Usage by Industry

Of all of the components of the American manufacturing industry, only a few are making significant use of industrial robots today. This section will briefly describe the robotics involvement of these industries, but two points should be kept in mind. First, some of these industries are more clearly focused than others. The aerospace industry is well-defined while non-metals light manufacturing is more of an organizational category than a coherent industry. Second, there is a significant amount of overlap between these industries. General Motors is clearly part of the automotive industry, but is also heavily involved in foundry activities. This type of cross-industry linkage can affect the level of technology implemented by a company as strongly as competition from other members of its own industry.

The industry descriptions that follow will present information on how long the industry has been involved with robots and factors that have encouraged and discouraged robotic implementation to provide a background for their current position. The current situation for each industry will be described, and illustrated by examples of typical or innovative implementations. Finally, a qualitative assessment of each industry's responsiveness to robotic developments will be given.

Automotive

The involvement of the American automotive industry with robots dates back to 1961, when General Motors installed a robot die casting unloader. While early industrial robots were limited in their capabilities, these capabilities were well matched to the demands of many tasks in automotive manufacturing. When the automotive industry began installing robotic spot welders, a pattern of robotic usage was established: simple robots performing simple tasks in high volume.

Many factors have encouraged the automotive industry to implement robots. The environment in which many assembly operations are performed is noisy and hazardous, while the jobs are monotonous and fatiguing. Escalating hourly costs for personnel and increasingly stringent OSHA requirements for work environment have steadily raised the cost of labor. Robots are seen as a method of holding costs down with the added benefit of improved quality, a matter of increasing concern among U.S. automobile manufacturers in the face of foreign competition.

A major barrier to robotic implementation in most industries is the high initial cost. This factor was less of a concern to automobile manufac-

turers because of the high volume of production; costs could be distributed over many production units. Furthermore, the automotive industry has, since the mid 1950's, accepted yearly retooling as a fact of life; thus the reluctance to invest in capital equipment has been less than in industries that retool on ten to fifteen year cycles.

Today, the automotive industry is the largest user of industrial robots in the U.S., with approximately 50% of America's installed robots. Spot welding is the most robotized application; at the end of 1983, almost 60% of General Motor's robots were spot welders. Machine loading is also heavily robotized, and spray painting robots are becoming common. The early pattern of simple robots performing simple tasks still holds true for the American automotive industry today.

However, this pattern in no way implies that this industry is complacent with respect to robots. In-house R&D efforts have kept the manufacturers abreast of new developments, and through-the-arc sensing robots for brazing body panels together and vision-equipped robots for assembly are being actively pursued. While the robots in American automotive factories may reflect a certain conservatism, this industry has demonstrated a willingness to implement new technology as soon as it considers the technology to be sufficiently mature.

Foundry

The foundry industry has been implementing robots since the early sixties. Early material handling robots were suitable for tasks like die unloading, the first foundry application for robots.

The major motivation for robotizing foundry work has been risk to human workers. Virtually every foundry process from pouring molten metal to the final cleaning of a casting exposes workers to heat, noise, fumes and dust. Robots have been used to reduce this exposure and also to relieve humans of the fatiguing tasks of manipulating hot, heavy metal parts.

The major barriers to increased robot utilization in foundry work have been limits of industrial robot flexibility and sensing. This is most clearly shown by the cleaning operations that until recently have remained a manual operation. The two major difficulties in automating the cleaning process have been the variability from casting to casting and the force or torque sensing required to control abrasive cut-off and grinding wheels.

The foundry industry today is one of the leading users of industrial robots in the U. S. Most of the robots in foundries are still performing material handling, with robotic unloading of cast aluminum transmission housings at Doehler-Jarvis being typical. Robots are also becoming common in investment casting where the quality of the cast part is largely determined by the consistency of the mold. Robots have demonstrated their ability to achieve greater consistency than humans, in addition to being able to handle mold trees several times heavier than humans.

The more demanding task of finishing castings is being performed by the Swedish firm of Kohlswa Jernverk using an ASEA model IRb-60 robot.

That installation uses torque and force sensing to control metal removal rate, and has demonstrated significant improvements in productivity over human performance due to the robot's ability to safely use higher powered grinding tools and to perform more consistently.

While the foundry industry may not be generally thought of as technologically innovative, with respect to robotics, they have established themselves as a major user of industrial robots. The implementations in this industry have overcome the problems associated with one of the harshest of the industrial environments, and, through sophisticated techniques like force controlled grinding, have demonstrated a willingness and ability to keep pace with developing technology.

Non-Metals Light Manufacturing

Non-metals light manufacturing shows its most conspicuous use of robots in the fabrication of plastic parts. The environment surrounding injection molding equipment is hot and fume-laden, and operator fatigue substantially reduces productivity. As with other industries, removal of personnel from a bad environment is a major incentive to introduce robots. Robotic implementation cost is the primary barrier in this industry; the small shops that make up a significant fraction of this industry cannot afford even a simple material handling robot. It is, therefore, not surprising that most of the robots in this industry are found in larger companies such as General Electric and Hoover.

Non-metals light manufacturing utilized about one sixth of American industrial robots by the end of 1982, and the bulk of them are used by larger companies in the injection molding process. A typical implementation is that used by Hoover in which a Prab-5800 robot unloads vacuum cleaner parts from the molding machine and presents them to a broaching machine for sprue removal. A more ambitious and better integrated project by General Electric involves automating their Louisville, KY dishwasher plant. In this plant, fully automatic injection molding machines are serviced by a computer-controlled conveyor system loaded and unloaded by robots produced by Cincinnati Milacron.

While it is not possible to categorize the technological responsiveness of this industry as a whole, it is clear that leaders like General Electric intend to keep up with new technology, if not to lead the way.

Electrical/Electronics

The electrical/electronics industry has long been taking advantage of automation in certain areas. Hard automation is firmly established for insertion of components into printed circuit boards in large batch electronics, while many of the processes involved in fabricating circuit boards (such as resist coating and etching) have been handled by automatic equipment.

The repetitive, labor-intensive nature of many tasks in this industry is considered an already solved problem. The large volume board stuffing

is being done with hard automation, at a speed that robots cannot hope to match, while small batch board stuffing is commonly performed outside the U.S., in countries with low labor cost.

Nevertheless, robots have penetrated this industry, and robots involved in the electrical/electronics industry represented about one tenth of the American industrial robots at the end of 1982. This penetration has been based on either using simple robots to replace humans in low demand but particularly unpleasant jobs at a lower cost, or by having the robots combine tasks normally performed by several people.

A typical example of the first approach is used by Northern Telcom Canada Ltd. to assemble terminal blocks. This low technology component is made by loading binding posts and a support block into a hot press, with the press applying heat and pressure to seal the posts into the support block. A robot made by PUMA is used, and while not significantly faster than a human operator, the robot can perform the task more economically by being able to operate continuously and by not requiring the special protective equipment needed by humans when handling hot (500°F) parts.

An example of a sophisticated application in which several tasks are combined is being performed by the Digital Equipment Corporation. A robotic cell is used to insert keycaps into keyboard assemblies, and the first task performed by the cell is inspection of the keycaps prior to assembly. Using an Autovision II vision system, the robot examines all incoming keycaps, rejecting any with incorrect legends or flaws, and loading acceptable keycaps into magazines for use by the second robot that performs the actual insertion. This combination of consistent inspection with actual assembly results in better quality control and is likely to set a pattern for assembly applications in this industry.

The electronics industry has not been very swift in implementing robots, due in part to many potential high volume applications already being performed by hard automation. However, the level of interest in sophisticated robots, such as vision-equipped assemblers, is very high. As robots with enhanced capabilities become available, this industry is ready and willing to use them.

Heavy Equipment Manufacturing

The heavy equipment manufacturing industry began their major involvement with robotics for arc welding in the late 70's. Their interest in robotic welding has been motivated by the same reasons as other industries: the cost and limited supply of skilled welders, and the long term health risks associated with the welding environment. This industry, more than most industries that use arc welding, has frequent need to weld thick work pieces which are difficult to weld and generally require flux-cored welding wire, which is particularly unpleasant to work with.

However, the heavy equipment industry operates in relatively small batches. This tends to make cost justification of robots more difficult because of fewer production units over which to distribute costs. For this industry, robots must show major productivity gains to be cost effective.

Nevertheless, robots have made significant penetrations into heavy equipment manufacturing, with this industry having approximately 10% of American industrial robots at the end of 1982. Welding is the most common application, as typified by use of Cincinnati Milacron T3 robots by the Locomotive Products Division of General Electric to weld large structural elements for diesel-electric locomotives. While the volume of production of these units may not be large, these robots have justified their installation by performing all of the needed welds in as little as half of the time required by humans. International Harvester has invested heavily in robots for production of their series 50 tractors. Nine machining cells, each equipped with two CNC turning centers that are loaded and unloaded by Cincinnati Milacron T3 robots, are used to turn gear blanks for the transmissions. A material handling robot produced by Prab is then used to transport ring gears through heat treating operations, and a DeVilbiss three-robot system spray paints much of the tractor chassis.

The above examples, coupled with the maintenance of in-house robotics R&D groups by other companies in this industry, such as John Deere, indicate that heavy equipment manufacturers are interested in and willing to make use of robots as the technology becomes available.

Aerospace

The involvement of the aerospace industry with industrial robots is relatively recent, compared to the automotive and foundry industries. In 1975, General Dynamics demonstrated the feasibility of a robotic work station for drilling aircraft wings. However, it was not until four years later that their first production robotic work station, funded by the Air Force MANTECH program, went into operation drilling pilot holes in composite materials. Early industrial robots had little impact on this industry, largely due to the need for a higher level of precision than those early robots offered.

There have been many factors that have encouraged the introduction of robots into aerospace manufacturing. The Air Force, through the MANTECH and TECHMOD programs, has made plain its interest in seeing its contractors implement robotics. The competitiveness of this industry requires the use of the most cost-effective manufacturing techniques available. Beyond cost-effectiveness, sheer precision of fabrication is critical in this industry; each new generation of aircraft is more demanding in manufacture than the prior one. Human techniques, using purpose-designed tools and carefully worked out methodologies, have kept up with demands for increasing precision, but may have reached the limits of development. On the other hand, robotic techniques are still in the early stages of development and show much room for rapid improvement. Health hazards represent an area of major concern in aerospace, especially with respect to many of the coatings that are commonly spray deposited. Robots offer an obvious way to remove humans from these hazards.

The major impediments to aerospace use of robots has been the need for high precision, coupled to the small batch sizes typical of the industry. Drilling and routing to the required precision requires the use of templates by today's robots, and fabrication and maintenance of templates for each different part used is an expensive proposition. This, with the high

initial cost of robots, results in a cost of implementation that can only be distributed over a limited number of units produced.

Today, the aerospace industry is only lightly penetrated by robots. Spray coating is the most common robotic application, with material handling and finishing (i.e. deburring and sanding) following. Some machining operations such as routing and drilling are being performed with robots, but templates are required. Typical spray coating applications are the use of Trallfa's robots by Fairchild Republic for painting parts of the A-10 and 747, while Martin Marietta is using a Cincinnati Milacron HT3 robot to spray ablator material on the external tanks of the space shuttle. In the field of material handling, Northrop is using a Cincinnati Milacron T3 to lay up plies for composite materials, an application in which robots are becoming prominent.

While the aerospace industry has been prominent in robotic R&D, it has been slow to implement robots in production. The reluctance to purchase expensive hardware for small batch production and limited lifetime contracts will probably continue to act as a deterrent to industrial robots in aerospace manufacturing.

2.5. A Composite Picture of Current Robotic Technology

The preceding sections plus Appendix A represent a fairly comprehensive assessment of the current robotic technology. What is intended to be achieved in this section is a balanced summary that can reasonably synthesize this substantial information base. The adopted approach to achieving this goal is to look at robotic applications in different industries across the board to highlight the major features and prominent trends. As a result of this assessment, current capabilities and technological barriers can be identified. They are, however, presented in Chapter 4 as an integral part of a technological forecast for ease of comparison instead of being included in this section.

One useful picture of the robotic technology can be obtained by analyzing the current applications according to their required level of capability sophistication. The objective in this exercise is just to arrive at a qualitative assessment of various applications as to where they are positioned in this "spectrum of technological sophistication". This picture will be helpful in understanding the present status and future potential developments of robotic technology along various application paths. It is extremely difficult to completely characterize the so-called "sophistication level". For the present limited purpose, several generic sensing and control capabilities are used as the key indicators to approximately define this spectrum. On the sensing axis, the sophistication level is envisioned to range from a single binary sensor to the sophisticated capability of real-time adaptive sensing. On the control axis, the sophistication level is characterized at the low end by a preprogrammed controller and at the high end by the capability of fully adaptive control and complete process planning.

In this spectrum, Figure 2-12 lists twelve application areas and shows where they are situated. In some cases, each application area is further divided into several generic categories that are distinguished

by their different capability requirements. This provides a more detailed picture of what is being achieved in each application area. Figure 2-12 also separates those applications which are now quite established in terms of industrial usage from those that are believed to only exist in isolated cases, as a prototype, or only as lab-scale model. The former are included in solid boxes while the latter characterized by boxes drawn with broken lines.

Another picture of the current robotics technology can be illustrated by studying the level of penetration of various robot applications in different industries. Since reliable numbers of robots actually being used in each industry are currently not available, it is more appropriate to describe the robot penetration in a rather qualitative manner. In Figure 2-13, the six industries which are presently known to use robots are listed in one axis against the other axis containing the twelve current robot applications. If an application has been well established in a significant number of industrial installations, then it is indicated by a solid circle. If an application is not reported in use anywhere and is unlikely to be adapted by that industry in the near future, then it is characterized by a hollow circle. Note that applications not relevant to a particular industry are indicated by a dash. Those applications that are marked by a half-filled circle belong to a group of applications that have been practiced in isolated cases or are being demonstrated with prototype units.

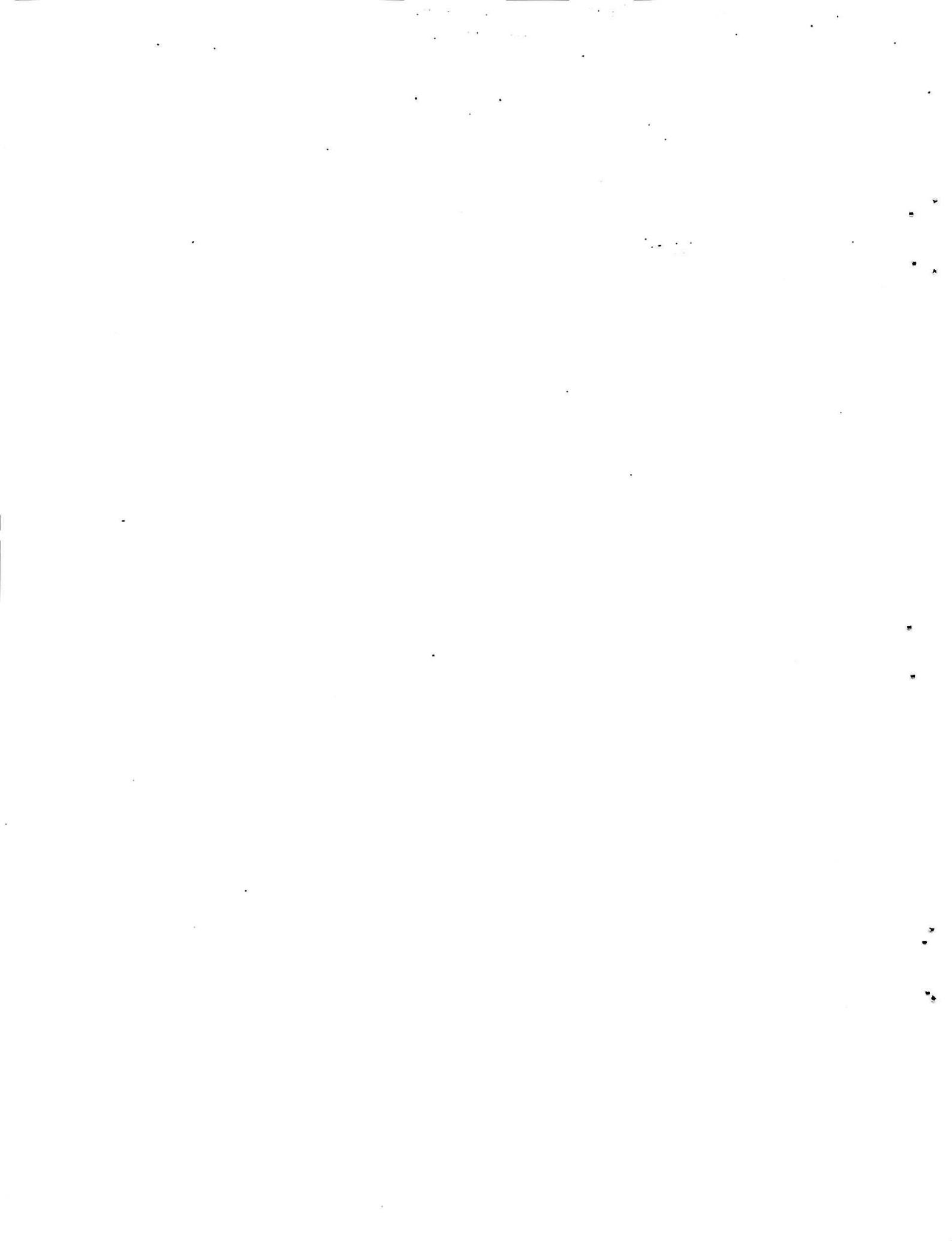
APPLICATIONS	SIMPLIFIED	SOPHISTICATED
Spot Welding	Binary Sensing Preprogrammed	Simple Vision (2D, 2-1/2D) Limited Adaptive Control
Arc Welding	One-Pass, Non-Adaptive Two Pass, Limited Adaptive Path Control	One Pass, Adaptive Path Control Limited Adaptive Process Control
Material Handling	Part Transfer in Known Location & Orientation, Tool Change	Location and Orientation for Transfer from a Known Area
Inspection		Part Recognition and Acquisition for Unstructured Supply (e.g. Bin Picking)
Assembly	Easy-Mating	Coarse Geometry, Surface Characterization Part or Assembly Completeness
Painting/Coating	NC Painter, Multiple Robots, Editable	Close-Fitting with Passive Compensation
Sealing/Bonding	Single Robot, Not Editable	Faster Close-Fitting With Active Compensation
Finishing	Simple Sealant Application	With Inspection and Adaptive Process Control
Investment Casting	Routing or Drilling with Template	With Flaw Repair
Die Casting	Investment Casting	Coarse Grinding with Force or Torque Sensing
Forging	Simple Die Casting	Routing or Drilling Without Template, High-Precision Grinding
Plastic Molding	Forging	Die Casting with Simple Inspection
	Plastic Injection Molding	

Figure 2-12: Established and Emergent Robotic Applications

APPLICATION INDUSTRY		SPOT WELDING	ARC WELDING	MATERIAL HANDLING	INSPECTION	ASSEMBLY	PAINTING/ COATING	SEALING/ COATING	FINISHING	INVESTMENT CASTING	DIE CASTING	FORGING	PLASTIC MOLDING
		●	●	●	●	●	●	●	●	●	●	●	○ ○
AUTOMOTIVE	—	—	●	●	●	●	●	●	●	●	●	●	○ ○
FOUNDRY	—	—	—	○	—	—	—	—	●	●	—	—	—
NON-METAL LIGHT MANUFACTURING	—	—	—	●	○	●	○	●	—	—	○	—	—
ELECTRICAL/ELECTRONICS	○	○	○	●	●	●	●	●	○	—	○	—	○ ○
HEAVY EQUIPMENT MANUFACTURING	○	○	●	●	○	○	○	○	●	○	○	○	○ ○
AEROSPACE	—	—	—	●	●	●	●	●	●	●	●	●	○ ○

● = significant penetration; ○ = moderate penetration or being introduced; ○ = no penetration;
 - = not relevant

Figure 2-13: Penetration of Current Robotic Applications in Various Industries



3. R&D Activities in Robotics

The status and future developments of robotics technology are strongly influenced by current and planned efforts in robotics R&D. A major part of the present study is, therefore, to conduct a comprehensive survey of R&D activities in robotics both inside and outside the U. S. It is an ambitious task which is achievable only when its objectives are well defined and its scope is properly bounded. It is with this perspective that a practical approach of stressing different aspects and focusing on more accessible information for various R&D programs is adopted. For example, one must seek different types of information on industrial R&D from those obtainable from government agencies. Even among government agencies, one should take into account different practices in information dissemination because of their differences in missions and traditions. Another situation that should be addressed is the question of what type of information is available and how one should cover R&D activities in Western Europe, Japan and the Soviet Bloc. In view of publications readily available, only the general R&D structure and directions in Western Europe and Japan are discussed while a closer examination is performed for the countries in the Soviet Bloc. In general, the differences in emphasized aspects and depth of treatment in our coverage of different R&D efforts will be clear to the reader.

In this chapter, the discussion of R&D activities is divided into two major sections, U. S. and foreign countries, with a smaller concluding section to highlight the key trends and directions in robotics R&D. In the U. S., information is organized into groups of institutions of a similar nature. They include government agencies, robotics producers and end-users, and the academic/non-profit community. Because of the special focus on Air Force activities, the federal agencies are classified into three sub-groups: Air Force, other DOD, and non-DOD federal. Discussion on foreign countries are divided into three groups: Japan, Western Europe, and the Soviet Bloc. Countries having an influential presence in robotics will receive more attention than the minor ones. At the end, a separate section is devoted to an integrated synthesis which is intended to bring out the key features and observations drawn from the preceding discussion.

3.1. U.S. Activities

3.1.1. Air Force

The Air Force funding efforts in robotics research encompass a broad spectrum of projects, from very basic research to the development and implementation of applied technologies. In practice, there is a rough division of funding sources into three categories: AFOSR, concerning primarily basic research, AFSC, funding applied research and developmental applications, and AFLC, dealing primarily with direct Air Force applications in the form of application studies. The following discussion will consider the individual robotics R&D programs of each of these offices and commands in turn, followed by a table summarizing the overall directions of Air Force R&D.

The structure of the AFOSR funding effort is based on the concept of "centers of excellence". The majority of AFOSR's R&D funds are channeled into a small number of institutions, which then become the focal point for many different areas of basic research. The University of Michigan, one of two centers of excellence, receives approximately \$1 million per year from AFOSR to conduct research on high performance manipulators, sensor subsystems, special-purpose computers and languages, knowledge systems, and sensor-based robot structures. All of these projects are integrated into a higher level study effort considering robot based manufacturing cells as building blocks for an integrated factory system. Stanford University, the other center of excellence, also receives about \$1 million per year to conduct a similar program with slightly more emphasis on basic sensor and sensor-based control research. There are two other recipients of AFOSR funding that, although not centers of excellence, represent a sizeable research effort: SRI International, a non-profit research lab which receives approximately \$200 thousand per year to conduct very broad-based research, including work on positioning accuracy and control; and Brigham Young University, which receives \$100 thousand per year to study microcomputer control of robots.

The AFSC effort in robotics R&D consists primarily of providing and/or managing the funds for robotics research in the MANSCIENCE, MANTECH, and TECHMOD programs. Each of these programs, while concerned with manufacturing productivity as a whole, have individual projects that specifically examine the emerging role of robotics in manufacturing. There is some variation in the focus of these programs; they range from very basic to more applied emphases. The MANSCIENCE Intelligent Task Automation project, or ITA, is the most fundamental of the three projects. ITA consists of two parallel projects, each performed by a different project team. The first project team, Honeywell, Stanford University, SRI, and Adept Technology, Inc., have as their goal the formation of basic hardware and software tools to be used in automated assembly. To date they have completed the design of a micromanipulator, force sensing fingers, 2-1/2 D vision hardware, and are close to completion of parallel force control strategies. To complete these studies, the Honeywell team was funded with \$3.35 million through the middle of FY85. The second team, Martin Marietta, Stanford University, ERIM, VPI, RPI, University of Massachusetts and McDonnell Douglas, are investigating the use of multi-arm systems, both in assembly and inspection operations. To date they have designed fiber optic and elastomeric tactile sensors, high speed feature detection algorithms, and a 3-level hierarchical planner. Almost complete are a laser scanner and several adaptive control schemes for servo controls. To complete this research, the Martin Marietta group was provided \$3.24 million, through the middle of FY85.

The MANTECH "Advanced Robotic Systems for Aerospace Batch Manufacturing" project is much more sharply focused on the goal of advancing application technology than MANSCIENCE's ITA project. The Advanced Robotic Systems project is divided into three tasks, with different contractors responsible for each task. Task A, conducted by McDonnell Douglas, involves the enhancement of their Machine Control Language (MCL) to make it compatible with a variety of CAD systems for off-line programming. Task B, conducted by RVSI, involves the development of a vision system. Task C, conducted

by Grumman Aircraft and Fairchild Aircraft, involves the control of drilling, trimming, and riveting procedures, aided in part by the off-line programming under development in Task A. Much of the robotic application technology developed through these and previous programs such as ICAM has been disseminated to industry both directly and through other Air Force and DoD programs such as TECHMOD. One TECHMOD program, the Rockwell International program to study the enhancement of mechanical tasks, has a sizable funding of its own, \$900 thousand.

Another source of the Air Force's funding efforts in robotics research and development is the AFLC. The AFLC is active both in supporting ALC-sponsored application development studies and in funding AFLC REP TECH efforts. The ALC studies are generally very application-specific, such as a Georgia Tech study to examine the feasibility of using robotics in automated packaging and warehousing, and a General Electric Aircraft Engine Group study of automated turbine blade inspection.

Although there is some overlap of interests, the above three robotics R&D efforts supported by the Air Force generally reflect the R&D missions of their sponsoring agencies. The AFOSR generally supports basic, unfocused research, in the form of block grants to establish focal points of robotics research. The AFSC supports a mixture of basic and developmental research to advance the state of manufacturing technology and productivity through its manufacturing science and manufacturing technology programs. Finally, the AFLC supports application-specific studies and efforts that help to influence AFLC process planning and activities. The above information on robotics R&D activities of the Air Force is tabulated in Figure 3-1.

3.1.2. Other DoD

Navy:

The Navy's efforts in robotics research and development follow a similar pattern to that of the Air Force. The Office of Naval Research, in a role analogous to the AFOSR, is the arm of the Navy concerned primarily with funding basic research projects in robotics. In addition, individual commands such as NAVSEA and NAVAIR are responsible for supporting application-oriented research and development projects consistent with their overall goals. This section presents the directions of Navy robotics R&D, highlighting ONR, NAVSEA, and NAVAIR. Finally, summaries of individual R&D efforts sponsored by each agency are presented.

Although ONR has not created "centers of excellence" as has AFOSR, there are two universities, the Massachusetts Institute of Technology and Carnegie-Mellon University, that have been very heavily funded by ONR. At MIT the funding has been weighted towards sensor research, while at CMU the R&D has mostly involved control research. ONR funding at other research institutions covers all aspects of robotic research: software control algorithms at New York University, University of Massachusetts and SRI, manipulator design and control at the University of Utah, sensor research at Yale University, Case Western Reserve University and the University of Rochester, and system performance issues at North Carolina State University,

Air Force Robotics R&D
(Sheet 1 of 2)

AFOSR: Unfocused sensor, manipulator and control studies

Performer/Estimated Support: University of Michigan (\$1M)

Research Areas:

- o Center of excellence: high performance manipulators, sensor subsystems, knowledge systems and problem solving, manufacturing cells.

Performer/Estimated Support: Stanford University (\$1M)

Research Areas:

- o Center of excellence: broad based research with emphasis on sensor hardware and sensor control.

Performer/Estimated Support: SRI, Intl. (\$200K)

Research Areas:

- o Broad based, emphasis on location and control.

Performer/Estimated Support: BYU (\$100K)

Research Areas:

- o Microcomputer control of robots

AFSC/MANSCIENCE (ITA): Developing robotic components for manufacturing applications.

Performer/Estimated Support: Honeywell/Stanford/SRI/Unimation (\$3.35M)

Research Areas:

- o Formation of basic hardware and software tools especially applicable to automated assembly.

Performer/Estimated Support: Martin Marietta/Stanford/ERIM/VPI/RPI/McDonnell Douglas (\$3.24M)

Research Areas:

- o Development of multi-arm systems for both assembly and inspection.

Air Force Robotics R&D
(Sheet 2 of 2)

AFSC/MANTECH (Advanced Robotic Systems): Implementing robotic technology to increase robotic manufacturing technology.

Performer: Fairchild Aircraft

Research Areas: o Robotic drilling and trimming

Performer: Grumman Aircraft

Research Areas: o Robotic drilling and riveting

Performer: McDonnell Douglas Aircraft

Research Areas: o Enhancement of MCL to provide off-line programming with CAD links

Performer: Robotic Vision Systems, Inc.

Research Areas: o advanced vision system

AFLC: Feasibility studies for specific applications.

Performer/Estimated Support: Georgia Tech (\$80K)

Research Areas: o Examine the feasibility of using robots in automated packaging and warehousing.

Performer/Estimated Support: General Electric (\$5.4M)

Research Areas: o Turbine blade inspection

Figure 3-1: Summary of Air Force Robotics R&D Activities

Purdue University, University of Maryland, and a Westinghouse research laboratory.

NAVSEA is currently supporting three robotics research projects, two involving issues of autonomous mobility, navigation, path planning and location control, and one involving welding techniques. The first project, located at the Naval Oceans Systems Center in San Diego, CA, is devoted to the design of a large scale autonomous mobile robot. The major research issues are obstacle avoidance and navigation by means of a hierarchical path planner. The second project, located at the Naval Surface Weapons Center in White Oak, MD, deals with a smaller scale mobile robot. The major research issue is navigation and decision making through use of coordinated sensory input. One projected application of this intelligent mobile robot is for use as a sentry. The third project is performed at the Philadelphia Naval Shipyard to develop and test adaptive seam welding techniques for ship hull fabrication. The focal point of the project is the design of a specialized welding end effector. Under a similar contract in 1983, the Philadelphia Naval Shipyard designed the Puma Arc Welding System (PAWS).

NAVAIR sponsors a very large effort to develop a robot to automate some aspects of refurbishing Navy planes. The Naval Air Rework Facility in San Diego, CA has funded the Southwest Research Institute (which should not be mistaken for the previously mentioned SRI, Intl.) with \$2.3 million to help them develop a robot that will perform the inspection and de-riveting operations necessary in rebuilding airplane wings. The robot will use vision and eddy current sensing to inspect each rivet, through available decision algorithms will decide whether it needs replacing, choose the correct drill parameters to properly drill the rivet, and then change tools to punch out the rivet. The final plan requires the robot to be on a mobile cart, so accurate positioning techniques will be necessary.

The above R&D activities are organized and presented in greater detail in Figures 3-2 and 3-3.

Army:

The Army's efforts in performing and supporting robotics research are divided into two distinct categories. One thrust involves research and development of robotics for use in the battlefield. This effort, beginning approximately four years ago, stemmed directly from HQ Army, and has been a cohesive, directed project to answer the question of how applicable will robotics and artificial intelligence be to battlefield situations between now and 1990 and 2000. The work began with feasibility studies such as that conducted by SRI in 1982 and continues currently with basic research to study the long-term possibilities of intelligent battlefield robots.

The second major thrust of Army robotics research is in manufacturing technology. Unlike the battlefield effort, the manufacturing technology effort is not centered in one place in the Army, but is divided between individual commands. Each command is responsible for organizing and conducting

Navy Robotics R&D (ONR)
(Sheet 1 OF 2)

PERFORMER	RESEARCH TOPIC
Carnegie Mellon University	<ul style="list-style-type: none">o Develop visual reasoning capabilitieso Design high power/mass ratio manipulators through use of Lagrangian modellingo Integrate sensor and end effector capabilities
Massachusetts Institute of Technology	<ul style="list-style-type: none">o Develop reasoning capabilities based on visual pattern recognitiono Improve welding techniques through better sensory integrationo Improve current tactile force sensing techniques and integration of information
New York University	<ul style="list-style-type: none">o Continuing ONR grant to develop special purpose, process oriented robot language. Funding: \$1.25M-\$1.5M/Yr
North Carolina State University	<ul style="list-style-type: none">o General study of measurement and interface technology, machine control and feedback control of machining processes
Purdue University	<ul style="list-style-type: none">o Wide range of research problems pertaining to precise engineering issues involved in a flexible manufacturing system
SRI, International	<ul style="list-style-type: none">o Development of process-oriented language
University of Rochester	<ul style="list-style-type: none">o Vision-pattern recognition techniques
University of Utah	<ul style="list-style-type: none">o Enhance control of three finger gripper through use of antagonistic tendons

Navy Robotics R&D (ONR)
(Sheet 2 OF 2)

PERFORMER	RESEARCH TOPIC
University of Maryland	<ul style="list-style-type: none">o Combined effort with NBS to develop error compensation analysis, defect identification analysis, experimental identification of dynamic characteristics
Yale University	<ul style="list-style-type: none">o Vision-scene understanding. Estimated funding: \$50K
Case Western Reserve	<ul style="list-style-type: none">o Various aspects of tactile sensing

Figure 3-2: Summary of Navy R&D Activities Sponsored by the Office of Naval Research

Navy Robotics R&D (NAVSEA and NAVAIR)

PERFORMER	RESEARCH TOPIC
Naval Ocean Systems Center/ NAVSEA	o Hierarchical path planner and obstacle avoidance control of large scale autonomous mobile robot. Estimated 1984 funding: \$120K
Naval Surface Weapons Center/ NAVSEA	o Decision making capabilities through use of integrated sensory input in autonomous mobile robot
Philadelphia Naval Shipyard/ NAVSEA	o Specialized welding end effector to enhance welding techniques for ship hull fabrication
Naval Air Rework Facility/ NAVAIR with Southwest Research Institute	o Develop and test a robot wing- de-riveter, incorporating advanced sensing and decision making capabili- ties

Figure 3-3: Summary of Navy R&D Activities Sponsored
by NAVSEA and NAVAIR

research in robotics that may be applicable to its operations. The research and development conducted through these programs, then, tends to be very applied, application-specific work.

One exception to the individual nature of the second thrust is a department-wide interest in painting/coating operations. The Tank-Automotive Command (TACOM) is the lead command, and is coordinating efforts with Depot System Command and the Troop Support Command. Chemical agent resistant coatings, and camouflage pattern painting requirements are an area of emphasis.

The Army is constantly increasing its commitment to robotics support; as development projects are completed new projects are budgeted. The current commitment, in terms of on-going 1984 projects and 1985 projects through apportionment review amounts to approximately \$3.1 million for manufacturing methods and technology efforts. The area of emphasis is primarily assembly and testing.

Presented in Figure 3-4 is a series of tables summarizing the individual R&D efforts of each of the active commands. The top section of each table identifies the command and gives a brief description of the thrust of the command's activities, the left-hand column describes each individual effort, and the right-hand column gives approximate funding levels of each project and outside performers, if appropriate.

DARPA:

DARPA's efforts in robotics research are divided into two thrusts: sensor-based control of robots for use in manufacturing, and the development of technologies necessary for an autonomous mobile vehicle. The mobile vehicle effort is in support of DARPA's long term goal of establishing a technology base for non-manufacturing military applications in maintenance logistics and weapons support. To this end, DARPA is concentrating its project funding in several areas: control of specialized manipulators, such as flexible or high-powered arms, and integration of advanced sensory input as a basis for both navigation and manipulator control. Specific topical areas supported by DARPA R&D funds are listed in Figure 3-5.

3.1.3. Non-DoD Federal

NASA:

The National Aeronautics and Space Administration has a significant funding program for robotics research as it applies to the problems of manipulating objects in space. The program is unique among federally-funded robotics programs as it is primarily concerned with integration, both within the robot in terms of integration of feedback control, and outside of the robot in terms of system input and output integration. Of a total funding effort of about \$1.5 million in 1984, more than 60% is devoted to control issues. The program as a whole is broken down into four topical project areas.

Army Robotics
(Sheet 1 of 2)

MICOM

MICOM's R&D thrust has been in the assembly of electronic missile parts.

- o Wire harness assembly. MICOM has been working to incorporate assembly and testing of the harness. Hughes and Boing Aerospace have been working with MICOM. Total funding has been \$2.15M.
- o Chip recognition. MICOM has been working for several years to incorporate material handling, optical pattern recognition, and assembly techniques into a single work cell. Prior efforts determined the system requirements. \$700K for system build requirements.

DESCOM

DESCOM's efforts in robotics R&D have centered around operations involved in the production and maintenance of tracked vehicles, such as spraying and coating, blast cleaning, and assembly/disassembly operations.

- o Automated blast cleaning. This is part of a three year effort to automate processes involved in reclaiming a double pin tracked vehicle. Also included are robotic disassembly of double pin tracks, reclamation of hardware from the tracks, welding of suspensions, and camouflage painting. \$582K for cleaning, \$299K for disassembly, \$325K for reclamation, \$795K for welding,

AMCCOM

AMCCOM has concentrated its robotics R&D on the issues involved in the manufacturing, inspection, and material handling of weapons, as well as sensor-based robotic applications requiring high precision.

- o Material handling for x-ray techniques. A robot would increase the quality control during inspection of Howitzer carriages by increasing the consistency of placement. \$709K in 1984

Army Robotics
(Sheet 2 of 2)

- o Robotic welding. Adaptive control is being developed for robotic welding of weapon components. \$291K for 1984
\$438K proposed for 1985.
- o Material handling and assembly of smaller caliber weapons. This is a feasibility and application study attempted to increase the production quality and volume. \$180K for 1984
- o Automated assembly and testing of IR transducer. This is a feasibility study to determine the requirements for such a system. \$1.946M proposed for 1985
- o Automated assembly of electronics module and top sensor. This feasibility study will determine the needs for automated assembly, highlighting optical and tactile sensors and control. \$1.018M proposed for 1985
- o Welding. There are two efforts in robotic arc welding. One is a development of general shop welding techniques at Rock Island Arsenal and the other is a continuation of ARRADCOM's welding project. \$285K for RIA
\$438K for the continuation of ARRADCOM; both for 1985.

AVSCOM

This command has begun a small effort to incorporate robotics into forging processes.

- o Adaptive control forging. This project will incorporate image sensing and a thermal video subsystem to gather data which will be used to control form and heating of the workpiece. \$215K in 1984
\$430K in 1985

Figure 3-4: Description of R&D Activities Funded by Various Army Command

DARPA Robotics R&D

<u>Performer</u>	<u>Topical Area</u>
	System Integration and Demonstration, Sensory control, and Advanced Mechanical Design
Honeywell, Martin Marietta	<ul style="list-style-type: none">o This is a collaboration with the Air Force's MANSCIENCE ITA project which is concentrating on hardware and software tools for assembly operations, as well as control of multiple arms.
Case Western Reserve University	<ul style="list-style-type: none">o DARPA shares funding with the Navy's ONR to perform various tactile sensing research, including haptic sensing.
Carnegie Mellon University	<ul style="list-style-type: none">o 3-D vision sensing for robot control.
Honeywell	<ul style="list-style-type: none">o Vision-range sensors and control systems.
Stanford University	<ul style="list-style-type: none">o End point control of flexible robots, path calculation and tracking hand control. Estimated 1984 funding: \$300K.
University of Utah	<ul style="list-style-type: none">o Electromagnetic machines with micro-actuators.
Duke University	<ul style="list-style-type: none">o Cooperation with Lord Corporation to produce compliant, anthropomorphic structures and actuators
	Robotic Support of Autonomous Mobile Vehicles
Carnegie Mellon University	<ul style="list-style-type: none">o DARPA has been funding CMU for an extended period of time to do research in the field of spatial reasoning.
University of Maryland, Yale University	<ul style="list-style-type: none">o DARPA is continuing a previous grant for work in spatial reasoning.
NBS, HEL	<ul style="list-style-type: none">o Sensor and control integration for robust, ammunition-handling robot
Rockwell International	<ul style="list-style-type: none">o Ultrasonic imaging sensors and algorithms for closed-loop control

Figure 3-5: R&D Areas Supported by DARPA

The first topic is vision processing. NASA funds the California Institute of Technology with approximately \$550 thousand per year to study the software algorithms and parallel processing architectures necessary to process visual information. The objective is to speed the processing so that information can be used for real-time control of the manipulator.

The second research topic that NASA is concerned with is man-machine interaction. NASA's ultimate goal of a combined teleoperated/expert system robot requires a complex interface between the expert system of the robot controller and the human input system. NASA funds the Jet Propulsion Laboratory, a NASA captive laboratory, with approximately \$250 thousand per year to study possible architectures for this man-machine interface.

The third research topic that interests NASA is supervisory control. This is essentially an extension of the first topic. Once the information from the vision sensor is processed, it must be incorporated into the robot control program to produce the desired response to the visual input. NASA funds JPL and indirectly both the University of Southern California and Stanford University with \$175 thousand per year to study efficient methods of supervisory control based on visual feedback information. Included in this grant is a study of the precise control of non-rigid robot arms conducted by Stanford University.

The fourth research topic supported by NASA is that of systems integration. In a remote, teleoperated/expert system robot, there will be many varied forms of system input and output. Input may come from on-board vision sensors, on-board position sensors, and remote teleoperation signals. Output may be in the form of position control, manipulator control, and teleoperation feedback signals. The robot controller must be sufficiently robust to handle precise coordination of the system inputs and outputs. NASA is currently funding the Langley Research Laboratory with \$500 thousand annually to study advanced system integration. There is a close coordination between Langley and the team developing the NBS system controller. In addition, there is a separate joint funding effort, about \$100 thousand per year in total, between NASA and the NBS to study space station robotics.

NASA sees their robotics R&D efforts growing in the future. With the exception of the Stanford University project, which should remain stable, funding in the other research areas is expected to increase in support of the growing NASA space station project. For example, FY1985 funding for the JPL man-machine interface work will increase from \$250 to \$350 thousand. These four R&D thrusts are summarized in Figure 3-6.

NBS:

The robotics program at the National Bureau of Standards is unique among federal robotics research programs in that the majority of the research is performed in-house with a large portion of the funding support received from other federal agencies. While divided into four distinct efforts, all of the robotics research conducted at the NBS has an underlying objective of formulating standards for the robotics industry. Work is concentrated not only on developing a robot subsystem but developing the subsystem to be compatible with other subsystems in a predictable manner. These

NASA Robotics R&D

PERFORMER	RESEARCH TOPIC	EST. SUPPORT
California Institute of Technology	<ul style="list-style-type: none"> o Vision information processing, Software algorithms and hard- ware parallel processing techniques 	\$550K
Jet Propulsion Lab	<ul style="list-style-type: none"> o Man-machine interface: control methods and architectures of a complex interactive man-machine interface (\$350K budgeted for (1985)) 	\$250K
JPL-Stanford-USC	<ul style="list-style-type: none"> o Supervisory control: incorpo- rating visual feedback response into robot control program o Control of non-rigid robot arms 	\$175K
Langley Research Lab	<ul style="list-style-type: none"> o Systems Integration: Complex integration of various inter- active inputs 	\$500K
	TOTAL	\$1,475k

Figure 3-6: Summary of Robotics R&D Programs
Supported by NASA

four efforts include software control hierarchies, vision sensing, tactile-sensored and quick-change grippers, and the establishment and support of the Automated Manufacturing Research Facility (AMRF).

The control system under development at NBS is designed to be both flexible and versatile. The system, based on the use of discrete "state tables" to define a world model, was originally designed to be used as a software development tool. Its emulation, simulation, single-step, and reverse-time capabilities will allow the programmer to write, test and debug robot controller software and make it ready for the shop floor with a single system. Other research institutes such as Westinghouse have used the system for their in-house non-proprietary research.

The emphasis of the vision research at NBS is to find a solution to the bin-picking problem, i.e. real-time acquisition of randomly-ordered parts in a factory environment. The novel technical aspect of this project is the use of two planes of structured light to illuminate the object. The use of the second plane of light gives information concerning the pitch and yaw of the object, in addition to the usual distance information obtained from one plane of light. The connection of this work to other work at NBS is the fact that the visual information is processed through the use of a world model. This world model is used as a means of standardizing information transmission protocols.

The gripper research at the NBS is divided into two projects: sensed grippers and quick-change grippers. Work in sensed grippers includes a two-finger gripper that is both force- and position-servoed, and the incorporation of tactile sensors and wrist position sensors into a complex gripper. Standardization of the mechanical and information interfaces is the focal point of the quick-change gripper research.

The largest robotics effort at the NBS is represented by the establishment of the AMRF. The aim of the facility is to provide a working factory environment for use as a developmental testbed. Many R&D projects have been conducted in this testbed: development of a universal calibration scheme, modification of a control system to include shop floor control, and robot-to-robot, robot-to-control, and robot-to-NC tool standardization techniques. Funding for the AMRF is not from a single source; the NBS solicits project funding from potential users of the technology under development. Members of industry have loaned or donated \$800 thousand worth of equipment for use in the AMRF. Contributions to this facility also come from DARPA through the Air Force ITA project, the Navy's ManTech program, and the Army's Aberdeen Proving Ground. In addition, universities have occasionally been invited to use the AMRF for their robotics research projects.

NSE:

The National Science Foundation has as one of its missions the support of basic and applied research at a fundamental level. In the field of robotics research, NSF has followed this principle and funded broad-based basic research in robotics. All aspects of robotic technology have been represented in the NSF program, from sensor and control research to issues

of robotic system performance. When individual project information is classified according to the control, sensing, manipulation and system performance taxonomy, however, overall qualitative R&D trends emphasized by this program become apparent.

The research area most heavily funded by the NSF is that of visual imaging. Program managers at the NSF believe this to be the fastest growing part of robotic technology, and plan to continue this policy. The current funding level of visual imaging projects is just over \$1 million per year, compared to a total annual budget of just over \$4 million in robotics. Other major areas of funding include tactile sensing and speech understanding with budgets of about \$300 thousand each, control research with an annual budget of about \$800 thousand, manipulator, actuator and end-effector research with a budget of approximately \$1 million per year, and system performance research with a funding level of about \$500 thousand per year. NSF is actually funding more basic research in robotics than the \$4 million total implies, because projects supported by other NSF programs are also relevant to the robotics field. For example, multiprocessing and VLSI research supported by the electrical engineering program and control theory research conducted through the systems group program are also useful in solving robot controller problems.

The short-term future of robotics funding at NSF is expected to remain steady with some increases in both current research areas and new areas. For example, a small effort of several hundred thousand dollars per year has just begun with the aim of studying possible applications of robots in the construction environment. Figure 3-7 presents a detailed breakdown of the NSF robotics programs by university and associated research issues in FY83.

3.1.4. Industry-Wide R&D Directions

So far, the U.S. R&D activities associated with the funding agencies have been reviewed. However, the R&D community of robotics also includes industrial laboratories, university research programs and several not-for-profit laboratories. With the exception of the industrial laboratories, they are primarily R&D performers and therefore play a relatively passive role in influencing the current emphasis and future directions of robotics R&D. The industrial laboratories may play a more active role since spending of their in-house research dollars is principally dictated by the corporate policy. It should be pointed out, however, that these industrial laboratories occasionally compete for government R&D funds. As a result, it is useful to assess R&D activities from the perspective of a performing group. Due to the limited scope of this chapter, R&D activities associated with the performing groups are described in Appendices B and C. Here the overall trends of industrial R&D are summarized, because the robot producers and end-users represent an independent force driving the general R&D directions.

The work performed by these industrial participants ranges from basic research to application development. There is, however, an approximate division among the industrial participants on the basis of their research

NSF Funding Analysis for FY83
(Sheet 1 of 5)

<u>Research Topic</u>	<u>Performer</u>	<u>Support Level</u> <u>(\$ K)</u>
<u>Sensing:</u>		
<u>Vision:</u>		
1) Picture algebra and picture data structures	Illinois Institute of Technology	42.1
2) Distance sensor for robotics	Kazuko Enterprises	113.9
3) Cost effective sensor systems for robots	Draper Labs	98.9
4) Structural and syntactic pattern recognition	Purdue University	105.1
5) Complex surface recognition for robot vision	University of Tenn	99.8
6) Fast pyramid algorithms for motion analysis and image	RPI	66.9
7) Incoherent optical processing using grating imaging	University of Michigan	20
8) Incoherent optical processing using grating imaging	Oakland University	25
9) Image processing for machine vision research	University of Wisconsin	36
10) Low-level functions of machine vision	Northeastern University	52
11) 3-D digitizer for creation of hierarchical models for robotic vision	VPI	7.2
12) Automatic visual inspection of printed circuit boards	SRI, Intl.	150

NSF Funding Analysis for FY83
(Sheet 2 of 5)

<u>Research Topic</u>	<u>Performer</u>	<u>Support Level</u>
13) Recognition of parts and their orientation	L.N.K.	110
14) Computational & geometric aspects of pattern recognition & vision	Johns Hopkins Univ.	40
15) Dynamic scene analysis	Univ. of Michigan	39.5
16) Structural matching and geometric reasoning for object classification	VPI	72.9
17) Theory and techniques for low-level vision	Univ. of Rochester	51.2
18) Integrated Architecture for industrial 3-D vision	Machine Intelligence Corporation	35
19) Multi resolution image analysis	Univ. of Maryland	157.4
	Subtotal	1,322.9

Tactile:

1) Automated tactile sensing	Case Western Reserve University	130.9
2) Integrated PVF2 transducer arrays	Stanford University	100
3) Thin film touch sensors	University of Texas	48
4) Robotics force sensor arrays	Bonneville Scientific	35
	Subtotal	313.9

Speech:

1) Parallelism in speech processing	Purdue University	88.9
2) Speech synthesis & recognition by computer	Louisiana State University	16.5

NSF Funding Analysis for FY83
(Sheet 3 of 5)

<u>Research Topic</u>	<u>Performer</u>	<u>Support Level</u>
3) Robust natural language processing	New York Univ.	60
4) Robust natural language processing	Burroughs Corporation	24.9
5) Knowledge acquisition in speech understanding	Carnegie Mellon Univ.	157
6) Automatic speech understanding	MIT	87
7) Natural language utterances	SRI, Intl.	94
8) Natural language processing	Duke University	1
9) Natural language information with database systems	Univ. of Pennsylvania	34.9
10) Research in natural language processing	Univ. of Pennsylvania	145.5
Subtotal		709.7

Control:

1) Dynamics and control of kinematically redundant systems	Ohio State Univ.	82.8
2) Advanced intelligence control for trainable manipulators	RPI	14.5
3) Intelligent bubble storage for robots	CMU	14.5
4) Research on geometric modelling	Univ. of Rochester	164.2
5) Robust control of mechanical motion	Cornell University	50.0
6) De-coupled motion of robot manipulator	Tennessee Technical University	48

NSF Funding Analysis for FY83
(Sheet 4 of 5)

<u>Research Topic</u>	<u>Performer</u>	<u>Support Level</u>
7) Development of evolutionary programming techniques	Wayne State Univ.	58
8) Strategies for data acquisition and utilization	Univ. of Pennsylvania	72.1
9) Decision making in advanced robotic systems	Polysystems Analysis	35
10) Advanced control of flexible manipulators	Scientific Systems	35
11) Computer graphics & design for robotics	Univ. of Alabama	37.1
12) Visual-tactile coordination for robot control	Univ. of Massachusetts	196.2
	Subtotal	937.9

Manipulation:

1) Mobile robots for manufacturing	Univ. of Virginia	99.9
2) Shape and dexterity of workspaces of manipulators	UCLA	48.0
3) Design conditions for robot manipulator and end-effector orientation	Arizona State Univ.	75.3
4) Local and global kinematics of multi-degree of freedom arm	Stanford University	75.0
5) Instantaneous kinematics and geometry of robot manipulators	Univ. of Florida	290.3
6) Bracing approach to lightweight robot arms	Georgia Tech	79.7
7) Investigation of novel robot arm	Oregon State Univ.	69.7

NSF Funding Analysis for FY83
(Sheet 5 of 5)

<u>Research Topic</u>	<u>Performer</u>	<u>Support Level</u>
8) Robotic material handling vehicle	University of Utah	48.0
9) Synthesis of spatial mechanism	Univ. of Florida	80
10) Equipment for precision machining systems	Univ. of Florida	49.3
11) Computer aided analysis of mechanical system	University of Iowa	17.6
12) Instantaneous space kinematics	Oklahoma State Univ.	56.4
13) Materials handling	Georgia Institute of Technology	25
	Subtotal	1,014.2

System Performance:

1) University/Industry Cooperative Research Centers		
1a) University of Rhode Island		220
1b) Georgia Tech		200
2) Optimization of robot mech. operation	Adv. Tech. & Research	35
3) Systems Design	Carnegie Mellon Univ.	73.1
	Subtotal	528.1
	TOTAL	4,826.7

Figure 3-7: Detailed Analysis of NSF Funding in Robotics

emphasis. Those companies that use robots but are not directly involved in the production of robots tend to concentrate their efforts on short-term application development, while those involved in the production of robots or robot components tend to perform more basic, long term research. A number of companies that produce robots for both internal use and external marketing, however, tend to perform a broader range of R&D. In the following, the individual research issues of each of the programs are identified and grouped into five generic research categories. From this grouping one can see overall industry-wide trends emerging in such research areas.

Mechanical:

In general, industrial research on mechanical robotic components is concentrated on improving existing components, such as the high-precision drives being developed by Allen Bradley, rather than on breaking new ground. Several exceptions are the three-wheeled mobile cart for the PUMA developed by Adept Technology, and the design of quick-change end effectors by GMF Robotics.

Control:

The area of robot control is one of the most active in industrial robotics research. There emerge three primary directions in this area of research, which are focused on process planning, integrated control of entire manufacturing processes, and sensor-based control. The development of robot programming languages is a unifying thread among these projects. For example, quite a few industrial laboratories are studying the language requirements for integrated control systems, sensor-based control systems, and process planning languages. Another common element among control research programs is the development of geometric models. These models are used as a basis for vision algorithms, trajectory planning and integration with CAD systems. There are several dominant industrial forces in the control field, which are represented among others by McDonnell Douglas, General Electric, Automatix, IBM, Cincinnati Milacron and GCA.

Sensing:

Sensing research, another very active field of industrial robotics research, is divided into two disciplines, vision sensing and tactile sensing. Tactile research and development generally takes the form of either short-term adaptation of binary sensors to application needs or long-term development of more advanced tactile capabilities. Leaders in the development of advanced tactile capabilities, such as increasing spatial resolution and shear force sensing, are the Lord Corporation, AT&T, and General Electric. Industrial vision sensor research, much like tactile research, currently has two directions, short-term application-specific and long-term developmental. The short-term vision research tends to concentrate on inspection processes, while the more general research is aimed at in-process control. Key industrial research laboratories working on inspection include Fairchild, Westinghouse, Digital Equipment

Corporation, and Northrop, while General Electric, General Motors, and Honeywell are studying more complex uses of vision in manufacturing processes. McDonnell Douglas, Fairchild, and IBM are all working on 3-D vision. In addition to tactile and vision sensing, there are other smaller sensing research efforts, such as the true volume sensor research conducted by RVSI.

System Performance:

Positioning and speed control are two important issues in industrial R&D. Both Northrop and General Dynamics are developing improved positioning capabilities for aerospace applications such as drilling and fabric lay-up, while Allen Bradley is developing increased speed capability for sealing/bonding applications.

Applications:

There is a great deal of application-specific research and development conducted in various industries. This research, due to its nature, covers a wide range of processes. However, there is currently a significant trend towards directing efforts into two processes, seam welding and assembly. Automatix and General Electric have been strong forces in the development of advanced seam welding techniques; while General Motors, IBM, Westinghouse, Adept Technology, Digital Equipment Corporation and General Electric concentrate more on robot assembly systems.

3.2. Foreign Activities

3.2.1. Japan

The robotics R&D efforts in Japan differ from those in the U.S. and Western Europe in that the Japanese government plays a more active role in influencing the general directions of the robotics technology. The structure of research institutions in Japan is similar to that of the U.S., consisting of four groups: national research institutions, public universities, private universities, and industrial laboratories. In general, research performed at the government-sponsored institutions has a fundamental orientation, while work at the private companies is of a more applied nature. Additionally, the quantity and scope of robotics research in Japan is quite extensive. For this reason, it would not be practical to present here a detailed list of each research project. For such an in-depth view of individual research projects underway in Japan, the reader is referred to any one of numerous reports written on the subject, (cf. "Trip Report; a Visit to Japan" by Thomas Binford of Stanford University). Rather, it is the intention of this report to provide a structured summary of the Japanese robotics R&D effort. As will be shown, the character of the robotics effort in Japan largely reflects its research climate as influenced by the government. The government funding strategies, as

well as national policies, have a direct effect on the specific research topics studied in Japan.

Funding Structure:

The general methods of research funding in Japan consist of government support of universities and national research institutions, government incentives to industry research, industry support of in-house research, and industry support of public and private research institutions. While these funding channels are qualitatively similar to those found in other countries such as the U.S., the relative levels of funding in each of these channels are different. Until April of 1982, the vast majority of funding for robotics research came from industry. In contrast to practice elsewhere, however, most of these funds tended to remain in-house, rather than be used to support university programs. In addition, government support, although on the rise, was on a much smaller scale. In 1980, for example, the government budget for robotics research was under \$2 million. Reversing this trend, the Japanese government initiated in 1982 a seven year, \$130 million program to advance the available robotic technology. A second national seven year program, the "Jupiter" project, began in 1983 with an estimated funding level of between \$55 and \$80 million. In addition to this increased funding, Japanese robotics R&D is also steered by the government policy of targeting its funding to specific applications to increase the effectiveness of the associated programs.

The Japanese industry's role in funding robotics R&D has been very similar to that played by industry in other countries, namely to drive research and development efforts in the direction of application-oriented issues. Unlike the industrial efforts elsewhere, however, industry in Japan as a rule does not cooperate closely with research institutions. For example, of a total 1980 industrial R&D budget of almost \$16 billion, only about \$1.3 billion, or approximately 8%, went to support universities and national research institutions, while the remaining 92% was used for in-house research and development.

Research Directions:

The current government policy regarding robotics research is to target those projects with a potential for private sector commercialization or for removing humans from dangerous environments. Under this guideline, the government keys their activities to the development of certain critical technologies, and funds those research projects heavily, even to the exclusion of other basic research issues. In this manner, the government hopes to realize the greatest gains in a specific technology with the least possible resource input. This is the same strategy that the government applied to the development of digital technology, which formed the basis of the great boom in the Japanese electronic industry. This targeting strategy today is manifest in the form of the two national programs. The overall objective of the first program is to improve the available generic robot technology so that individual industrial companies can modernize and automate their facilities. The goal of the second program, the Jupiter project, is to improve those robot technologies necessary to remove human workers from critical or hazardous environments, such as nuclear, undersea, and rescue situations.

The divergence of the industrial programs from national institution and university programs is evident not only in the funding trends but also in the research areas addressed. For instance, one of the targeted areas of research in the 1982 government project is actuator technology, or "mechatronics". In contrast, analysis of patent information for the past several years reveals that development of actuator technology in private industry is relatively inactive. This segregation of research projects, combined with at least a minimal level of communication between the two types of research groups, leads to a very well rounded and complete research and developmental technology base.

Specific Research Topics:

As mentioned earlier, there are currently two national robotics programs running in parallel in Japan: one began in 1982, and the Jupiter project began in 1983. While the goals of these projects are different, the technologies studied in the projects are similar. The highlighted issues of the first project include the sophistication and miniaturization of vision sensing systems, sophistication of touch sensor technology, and various aspects of actuator technology, or mechatronics. The scope of the Jupiter project is more extensive, incorporating those issues previously targeted and including many more. The following table (see Figure 3-8) is a list of those technological issues targeted by The Japanese government as key barriers to the widespread use of robotics for critical or hazardous work. Over the course of the Jupiter project research in each of these areas will be funded by the government. Numbers in parentheses indicate the number of projects already underway in those areas as of the beginning of the program in 1983. A topic with no number indicates that although the program has targeted that area as important, no projects had been initiated as of the start of the project.

In summary, the Japanese robotics effort can be characterized by the institutional and funding structures within the research community, the overall research directions, and the specific research topics studied. The institutional structure, although similar to that of the U.S., is funded in a segregated manner, with industry supporting in-house applied research almost exclusively, and government targeting funds for specific areas of basic research. These research areas are directed towards the key issues necessary for the advancement of specific goals, such as improving generic robotic technology for manufacturing and industrial needs, or for improving those technologies that will enable robotic applications for hazardous and critical work, as seen in the individual topic areas of research studied under the Jupiter project.

3.2.2. Western Europe

United Kingdom:

The outstanding feature of robotics R&D in the U.K. is that it is driven to a large extent by engineering and application thrusts, rather than by the scientific issues as in the U.S. and Japan. This comes about

Japanese Robotics R&D
(Sheet 1 of 3)

Mechanical:

- Actuator (27 Actuator/Manipulator)
 - o Compact AC servo and microservo motors
 - o Weight/Output ratio approximately equal to muscles
 - o 3 axis actuator
 - o High capacity batteries for mobile robots
- Manipulator (27 Actuator/Manipulator)
 - o Light, multi-articulated arms incorporating advanced materials
 - o Improvement of 3-roll wrist
 - o Master/slave manipulator system
- End Effector (2)
 - o 3-fingered dextrous hand
 - o Force sensed gripper
- Locomotion (30)
 - o Mobile robot capable of navigating in complex environment
 - o Multi-ped robot capable of climbing stairs, walls, pipes and trenches
- Others (5)

Control:

- Hardware
 - o High-speed dedicated processors
 - o Parallel processing architectures

Japanese Robotics R&D
(Sheet 2 of 3)

- Software (59 Language, 9 Path Control)
 - o Hierarchical control algorithms, both within the robot and for system integration and task organization
 - o Task specific, skilled algorithms, such as control for assembly using gripper force
 - o Acquiring and using a knowledge base
 - o Standard programming language and operating system for 16-bit processor environment
 - o Language capable of voice command recognition
 - o Autonomous control for mobile robots, navigation
 - o In-process fault diagnosis

Sensing:

- Vision (15)
 - o Miniaturization of camera system
 - o Fast pattern recognition, goal of <0.1 Sec.
 - o Increased spatial resolution, goal of 4k x 4k element semi-conductor
 - o High speed processing system for tracking motion
 - o 3-D vision
- Tactile
 - o Flexible matrix touch sensor with high spatial resolution
 - o Shear sensor
 - o Force-displacement sensor
- Hearing (5)
 - o Continuous voice recognition of unspecified speaker
 - o Direction of abnormal in-process sounds

**Japanese Robotics R&D
(Sheet 3 of 3)**

- Proximity/Ranging
 - o Laser ranging system
- Others (30)
 - o Light, compact gyroscope for robot

Application:

- Assembly
- Finishing

Adapted from:

- JIRA, "Report on Research and Development trends by Universities, National and Public Institute, etc, regarding Industrial Robots" (March 1983); and
- JIRA, "Report of Long-Term Forecast on Technology of Industrial Robots" (March 1983)

**Figure 3-9: Robotics R&D Areas of Concentration
in Japan**

mainly due to the different character of government funding programs in the U.K. An important characteristic of the U.K. government policy is the push for immediate industrial modernization. There is a willingness on the part of the government to fund industrial modernization efforts that have a short time frame. Specifically, one program currently underway provides up to 33% of the cost of feasibility studies, application, and manufacture of robots to interested companies. This attitude extends to university research as well. One of the major university R&D programs in the robotics field was created in 1980 through the Science and Engineering Research Council (SERC). The important aspect of this program is that it is a cooperative effort between government and industry; half of the resources come from the government and the other half from industry. This funding structure, compounded by the fact that there is very little military support to the universities for basic research, creates a heavy dependence on industry. This dependence on industry pulls robotics research in the direction of solving short-term, application-oriented problems, rather than building a base of scientific knowledge from fundamental research. A detailed examination of the focused areas of research for some of the major institutions reveals this application-oriented characteristic.

Of the universities that are active in fundamental robotics research, three have programs that have been sizable and successful in creating a groundwork for robotics research: Edinburgh, Warwick and Oxford. The work at Edinburgh has concentrated on studying the kinematics and geometry of assembly operations, as well as the development of the robot language RAPT. This language has since been refined by GEC, Britain's leading robot manufacturer. Although in the last several years some key researchers have left Edinburgh to work in the U.S., leaving the program with few people and a low funding scale, there is still significant theoretical work being done there. At Warwick University the work has concentrated on mobile robots. Warwick hopes to consolidate some SERC funding and establish a nationwide center for research in mobile robots and particularly automated warehousing. The research at Oxford university is more application-oriented than work at Edinburgh and Warwick, concentrating on automating factory processes such as arc welding. Structured light and adaptive control are the highlighted issues there. The structured light system, similar to that designed by Automatix of the U.S. has been successfully demonstrated and is rapidly penetrating industry. There are a number of universities with smaller, usually single-focus programs, such as Imperial College, working on adaptive and logic control, Liverpool, working on control issues and the University of London, working on vision.

The industrial R&D effort in the U.K., as mentioned earlier, is directed toward solving application-oriented problems. The largest industrial R&D effort comes from GEC. GEC has established two separate in-house research laboratories, the Hirst Research Laboratory, conducting research in 3-D stereo-vision and tactile sensing, and the Great Baddow Laboratory, which is working on adapting RAPT for process planning, as well as a very stiff, accurate robot called GADFLY. There are several smaller efforts centered in the aerospace industry. Some of these companies are funded heavily with military money to study robotic vision. On a smaller scale, there are many industrial participants performing in-house application specific R&D in robotics. Most of these efforts are at least partially connected with, if not subsidized by, government programs to advance the

implementation of robotic technology. As an example of this cooperation between industry and government, one should also include the Production Engineering Research Association (PERA). In addition to being a key performer of industrial robotics R&D, PERA is the most important U.K. supplier of the government-funded Robot Advisory Service. Finally, the National Engineering Laboratory (NEL) in Scotland is a key factor both in performing robotic R&D and disseminating the emerging technology to industry.

In summary, it can be seen that the overall thrust of robotics research in the U.K. is directed toward short-term modernization of manufacturing processes, rather than long-term fundamental research. This is due in general to the overall industrial climate of the U.K. and specifically to the types of funding programs that the government and industry support.

France:

France has recently embarked upon a major R&D effort to upgrade the general level of manufacturing technology. Included in this effort is a three year, \$350 million program from 1983 to 1985 to fund robotics research, train robotics specialists and promote the implementation of robotics in industry. Robotics R&D in France then is characterized by a heavy support program from the government, with the aim of building a solid scientific knowledge base. For this reason, government-sponsored research programs tend towards basic research, while industrial support drives the more applied, developmental research. The end result is a very well rounded robotics program.

The robotics research institutions in France consist of three types: government in-house laboratories, industrial in-house laboratories, and university laboratories. Government funding generally flows from government agencies to all three types of laboratories, while industrial funding remains for the most part in-house, with some channeled to university programs. Although this structure appears similar to that of the U.S., there are two notable differences. The first is that there is much less cooperation between industry and universities, in the sense that industry generally expects to get finished products from university testbeds, as opposed to merely ideas and concepts. The second difference is that there is a much stronger emphasis on in-house government research. For example, CNRS (the National Scientific Research Council) operates several major laboratories with an emphasis on robotics, including INRIA (National Research Institute on Computer Science and Control) in Paris, LAAS (Computer Science and Systems Analysis Laboratory) in Toulouse, and IMAG (Computer Science and Applied Mathematics Laboratory of Grenoble) in Grenoble. In addition to CNRS laboratories, there are other in-house government robotics laboratories, such as the one operated by the CEA (Atomic Energy Commission) and the recently established National Robotics Laboratory in Marseilles. CNRS is responsible not only for funding but also for initiating research programs. The thrust of one such program is to advance automated assembly techniques.

The industrial R&D effort in France has centered for the most part around the automotive industry. The largest effort in this field has

been on the part of Renault. Renault began building robots in-house for its automotive assembly line, and continues to design robots and controllers for other users in industry. One characteristic of Renault's efforts has been a close collaboration with the government-run INRIA laboratory. With regard to universities, the Technical University of Compiègne and the University of Lille represent the two largest robotics programs in French universities.

Figure 3-9 summarizes the key research areas sponsored by the French R&D community on robotics. From the detailed picture of research topical areas, it can be seen that the thrust of robotics research in France has been to build a solid base of fundamental research. This research is performed within a climate of heavy government support in an overall effort to upgrade the manufacturing technology base of the country.

West Germany:

Unlike robotics efforts in other countries, robotics research in West Germany is much more centralized. At the center of the German robotics effort, performing the majority of the research and development, are the Fraunhofer Gesellschaft Institutes. The Fraunhofer Institutes are actually a series of twenty-six individual not-for-profit research institutions, funded one third by general government block grants, one third from industries, and one third from specific government contracts. Three of the institutes which are very active in robotics work are the IITB in Karlsruhe, the IPA in Stuttgart, and the IPA in Berlin. Several universities worth noting here because of the large size of their robotics programs are Karlsruhe University, the University of Aachen and the University of Stuttgart. In the industrial sector, there are a large number of robot producers, such as KUKA and Volkswagen, that have substantial programs of application- and production-oriented robotics research.

The IITB in Karlsruhe is currently working on three robotics projects. The first project involves using structured light to guide robotic arc welding. The research carried out has been a forerunner to the vision work done at Oxford University. The second project at the IITB is called the "very advanced industrial robot". Although the name is reminiscent of the Japanese "fifth generation computer" project, the IITB project involves merely a multi-sensored robot. The emphasis of the project is modularity and sensor-based control through the use of a high-level language. The third project is focused on machine vision. The novel aspect of this project is that its thrust is not to improve software but to produce a hardware-intensive, fast, marketable vision module.

There are approximately 30 people working in various robotics projects at the IPA in Stuttgart. One of the larger projects at the IPA has been the development of a robot measuring station. The station is designed to assess various functional capabilities of new robots. Another large robotics project at the IPA involves the coordination of a flexible manufacturing cell. While in the past the cell has had few sensors, current work involves adapting various kinds of vision and tactile sensors for use in the cell.

French Robotics R&D

INSTITUTION	FOCUSED AREA OF RESEARCH
<u>Universities</u>	
Technical University of Compiegne	<ul style="list-style-type: none"> o Real time vision processing, geometric data-base design, systems integration
University of Lille	<ul style="list-style-type: none"> o Basic research issues
<u>Government In-House Labs</u>	
LIMSI	<ul style="list-style-type: none"> o Manipulation for assembly, visual inspection, work cell integration
INRIA	<ul style="list-style-type: none"> o Perception: Laser illumination for assembly & inspection, 3-D vision, obstacle avoidance
LAAS	<ul style="list-style-type: none"> o Sensors and sensor data processing, systems integration: control for assembly, perception, planning ARA Project, mobile robot
IMAG	<ul style="list-style-type: none"> o Robot programming tools, (developed language LM) automatic assembly, expert manufacturing planning, vision: gray scale & 3-D using laser
CGA	<ul style="list-style-type: none"> o Inspection of nuclear facilities
LAM	<ul style="list-style-type: none"> o Modelling and control of manipulators, simple vision, coordination of multiple robots
DERA	<ul style="list-style-type: none"> o Control systems; flexible automation and robots for space systems
National Robotics Lab	<ul style="list-style-type: none"> o Various applied research issues
<u>Industry Labs</u>	
Renault	<ul style="list-style-type: none"> o Industrial robot research vision for inspection, controllers, process planning
MATRA	<ul style="list-style-type: none"> o fast vision module o assembly robots

Figure 3-8: Robotics R&D Directions in France

The robotics program at the IPA in Berlin is also large, consisting of many different robotics projects. Three of the major efforts are devoted to controllers, modeling, and adaptive sensor control. The controller project involves designing a controller for the German-produced KUKA robot. This controller is also used by the Daimler-Benz automobile company to do highly accurate and difficult to reach spot welding tasks. The modeling project consists of the development of COMPAC, a package for 3-D surface modeling. The sensor-based control project emphasizes arc welding. The research issue there is how to use magnetic sensing of the arc parameters to guide the robot arc welding gun.

The three largest university robotics efforts in West Germany reside at Karlsruhe University, the University of Aachen and the University of Stuttgart. At Karlsruhe University, the robotics program has employed as many as 25 people. The research issues under study include several different types of vision systems, a portable robot programming system, and a highly instrumented robot gripper. Robotics research at the University of Aachen is divided into two directions. One direction is in robot language development, similar to the RAPT development effort at Edinburgh and GEC. The second direction has been the development of a modular robot. The aim of the project is to develop a robot constructed of standard, modular parts, i.e. interchangeable actuators and linkages, as well as the software to control it. They have in fact marketed a working version of this modular robot. The third sizable university robotics effort is at the University of Stuttgart. The Stuttgart program is centered on sensor-based control of manufacturing processes, specifically in welding and grinding operations.

West German industrial R&D is driven by in-house application problems. The best example of this is found at Volkswagen. Volkswagen started by using imported robots in their automobile assembly plant. As the need for application-specific developmental R&D rose, Volkswagen stopped modifying foreign robots and began producing their own robots. This effort has grown significantly, and now Volkswagen is marketing several different lines of robots worldwide.

One additional point should be mentioned concerning the institutional structure of robotics R&D in West Germany. Each of the three Fraunhofer institutes mentioned is closely associated with a university in its respective city. In fact, the university professors who are responsible for the robotics programs at the universities are also directors of the institutes. This powerful link provides for rapid and effective diffusion of emerging technologies into industry.

In summary, the overall thrust of West German robotics R&D is very application-oriented, much more so than, for example, the French effort. This is partially due to the funding structure of the German robotics R&D. In a situation similar to that of the U.K., the research institutions in West Germany are heavily dependent on industry and short-term government contracts for their support. This has pulled the research more towards the development of robotic applications.

Other Western European Countries:

Robotics R&D efforts throughout the remainder of Western Europe take the form of scattered programs, with no cohesive structure or overall research goals. In these countries there are one or two isolated research efforts, but little or no evidence of country wide policies or programs.

After France, West Germany and the U.K., the next largest robotics R&D program is in Sweden. Robotics research in Sweden is focused on industrial development, with the largest program conducted by ASEA, a manufacturer of one of the most accurate robots built. The majority of ASEA's research is dedicated to application oriented programming. In addition, there are several trade institutions, such as a welding institute, that study the application of robotics relevant to their field of interest. The above-mentioned welding institute is currently studying the use of vision to monitor the bead to control arc welding processes.

The character of the robotics R&D effort in Norway is similar to that in Sweden. Trallfa, the leading manufacturer of spray painting robots worldwide, conducts in-house research and development, as well as cooperates closely with research institutions such as the Central Institute for Industrial Research, the National Institute of Technology, the Roaglund Research Foundation, and the Christian Michelsen Institute. The robotics research issues highlighted in these programs are mainly in control applications.

The robotic research in Italy follows a similar pattern to that in Sweden and Norway. Several medium-sized robot manufacturers and end-users, Olivetti, DEA, and Fiat specifically, fund their own in-house developmental research and cooperate with university research institutions, such as the Milan Polytechnic Institute. Work at the Milan Polytechnic, the oldest and largest robotics research program in Italy, includes natural language understanding, automated problem solving, and sensor-based control. Sharing the resources of the Milan Polytechnic has been the Laboratorio per Ricerche de Dinamica dei Sistemi e di Bioingegneria (LADSEB), a national institute for bioengineering and systems dynamics research. LADSEB has been working on robot programming languages, geometric modeling and robot actuator control.

The Belgian robotics R&D effort is typical of the smaller robotics programs in Western Europe. There is very little industrial involvement, as the robotics industry is struggling to overcome pressures from imported technology, and has little capital to support university programs. The government supports robotic research and development, but at a low and uncertain level. The one very active research institution is the Katholieke Universiteit Leuven, where current robotics projects include force sensing, active compliance, sensor-based control and programming language development.

Other Western European countries in which there is scattered work in robotics research include The Netherlands, Switzerland and Finland. The Dutch government supports the robotic industry as a whole with approximately \$5.5 million in the form of incentives for industry to cooperate closely with research institutions, robotics education programs, and subsidies and loans to stimulate pilot demonstrations of robotics

and flexible manufacturing. Robotics R&D in Switzerland is for the most part performed at two technical institutes, the Zurich Federal Institute of Technology and the Lausanne Ecole Polytechnique Federale. Funding for these programs, which are directed largely towards basic research issues, comes from a close cooperation with industry, as well as from limited government funds. It should be noted that research and development in Finland is not funded by the government, nor does the government engage in administrative practices for the industry's protection.

3.2.3. Soviet Bloc

The Eastern European nations have been involved in robotics research for over 20 years, with the first industrial robot being produced in 1971. The reasons for their interest in robots are similar to those of the West, namely the problems of labor shortages, training requirements, dangerous and monotonous jobs and the need for higher quality products at reduced costs.

This section presents a sample of the institutions involved in robotics R&D, with selected highlights of the research conducted at each institution. Additionally, when possible the areas of future R&D efforts that individual countries can be expected to follow will be included. Before describing the efforts undertaken by specific countries, it should be pointed out that, with the exception of Yugoslavia, all of the countries to be mentioned belong to the Council for Economic Mutual Assistance (CEMA), which coordinates joint R&D efforts to unify the design of robots. These efforts are carried out through the Experimental Machine Tool Research Institute of CEMA.

Although the Eastern European countries have been involved in robotics for some time, at present the CEMA members are approximately a decade behind the West in robot technology. This is due in a large part to lack of digital microprocessors, limiting the capabilities of commercialized robots largely to pick and place operations. The shortage of computers also affects research in such a way that the efforts are confined to theoretical research. This problem of lack of computers is not as acute in Yugoslavia, which has a closer relationship with the West. The Yugoslav robots are, with one exception, controlled by microprocessors including the Intel 8080 microprocessor. Due to their advantage in computing power they are considered a leader in Eastern European robotics.

The deficiency in computing power of the CEMA nations is expected to be significantly alleviated in 5 to 7 years. By that time the Soviet electronics industry would be capable of manufacturing precision digital electronics. This improvement will allow the production of more complex adaptive and artificial intelligence control systems, thus greatly increasing robotic capabilities. It will also presumably drive their previously theoretical research into a more practical direction.

Soviet Union:

Institutions:

Research in Soviet robotics is coordinated by the Council on the Theory and Design of Robots and Manipulator Devices. The Leningrad Polytechnical Institute's Special Design Bureau of Technical Cybernetics has been designated as the leading institution for research and development of robots. The Bureau oversees over 50 research institutions and manufacturers in the Leningrad area in robotics R&D. Members include the Pozitron Production Corporation, the Optical Design and Precision Mechanics Bureau, the Leningrad Institute of Aviation Instrument Building, the Electrotechnical Institute and the Refrigeration Industry.

There are several leading academic institutions in Soviet robotics research other than the Leningrad Polytechnical Institute (LPI). These include the University of Kiev's Institute of Cybernetics, the University of Moscow's Institute of Applied Mathematics, and the Moscow State University's Institute of Mechanics.

The education of robotics specialists was made the responsibility of the Ministry of Higher Education and the State Professional Educational Authority. The first universities to teach a robotics engineering curriculum were the Bauman Technical Institute in Moscow and the Leningrad Mechanical Institute. Presently, most major engineering schools offer courses in robotic technology.

R&D Focuses:

Soviet robotics R&D currently involves a wide spectrum of research areas. The general topics under consideration are robot control, sensing, mechanical structures and applications. R&D is on-going in all of these areas, but it is limited by a lack of computers and integration capacity. At present the Soviet electronics industry is not capable of producing precision electronics. There are a limited number of 8-bit microprocessors, mostly copies of American chips, but the Soviets lack the ability to program them effectively.

Because the robot controller depends so heavily on electronic computing power, this area has been most affected by the lag in Soviet digital technology. As a result of this, research in the area of control has been for the most part on a very theoretical level. Examples of such work are in the development of mathematical systems to aid in programming control systems, and in the verification of various mathematical theorems in AI research at the University of Kiev. Another topic of theoretical research influenced by the lack of computers is a proposed algorithm which tracks and approximates the contours of objects without computers but rather with logic conditions.

Although most control system research is conducted on a theoretical basis, some experimental R&D is performed. One such example is a robot at LPI which uses digital control. It is operated by two computers, an ASVT M600 and a Minsk 32, with a five-level hierarchical control system.

The robot has demonstrated the ability to grasp irregularly-shaped objects, negotiate obstacles and assemble parts. Other robots with advanced control systems include a three-legged walking robot at the Computer Center of the Academy of Sciences and the OSU Hexapod, a six-legged walking robot developed at the Moscow State University. This robot is being developed for the timber industry with the help of Dr. McGhee of the Ohio State University.

The institute most active in robotic sensor research has been LPI. A variety of sensors have been developed at LPI which include TV vision, laser vision, ultrasonic sensing, tactile sensing, force sensing, and hearing. An example of a robot at LPI employing sensory capabilities is LPI-2, which has TV vision and an ultrasonic locator for finding objects, as well as two grippers with force and tactile sensors. Another LPI robot is a TSIKLON-3B robot with hearing capabilities. It can respond to 200 spoken commands such as, "open gripper" and "rotate waist". This capacity to respond to spoken commands represents a big step for the Soviets in overcoming their lack of programming ability.

In addition to LPI, vision research is conducted at the Leningrad Institute of Aviation Instrument Building in visual identification for sorting of objects on a moving conveyor belt. Researchers at the University of Moscow are conducting research in the theory of image identification. Additionally, the University of Kiev has been a leader in Soviet vision sensing research.

The Soviet research in mechanical systems is primarily focused in the areas of actuators, grippers and modularization. Because electric drives are the most common type of actuator in the Soviet Union, research has concentrated on their refinement and improvement. Harmonic drives are under study as well, presumably because of minimal weight and size and a self-locking characteristic preventing unwanted joint movements.

Gripper development is an active field of research at LPI. An example of current work is the development of soft grippers, which are capable of handling sensitive objects such as light bulbs. Another gripper effort involves an electromagnetic gripper. This gripper has reduced search and pick-up time for a particular experiment from 702 sec. to 40 sec. by "grasping" an object in a closely packed container with an electromagnet instead of a conventional gripper.

Development efforts are being made in robot modularization. The modular approach is being pursued by manufacturers to allow several robots to be constructed from standard module parts. This approach allows, for example, over 100 arms to be made from 16 different modules.

Research in industrial applications is concerned primarily with the development of standardized flexible manufacturing facilities. The goal is to achieve high flexibility and automation in manufacturing processes. Again, the institution which appears to be involved most heavily in application R&D is LPI.

Funding information on Soviet robotics R&D was not available; however, an estimated measure of the level of effort can be determined from the

number of research institutions and employed researchers. From an estimate by Kent Schlussel of the U.S. Army Foreign Science and Technology Center, there are approximately 60 research institutes active in robotics research. The largest of these is LPI, with about 400 researchers. Following LPI are the University of Kiev and Moscow State University, each with approximately 200 researchers.

Future Directions:

Perhaps the best prediction for future Soviet robotics R&D comes from the Deputy Chief Designer of the State Committee on Science and Technology, P.N. Belyanin. He indicates that due to the increase in the availability of microprocessors Soviet robotics will utilize adaptive control to a greater extent and will develop single computers for control of several robots. This advance can be expected some time after the Soviet electronics industry develops the capability to produce reliable microprocessors, which is expected in 5 to 7 years. It can be assumed that with greater adaptive control capabilities robots will be assigned more complex tasks, such as assembly. Further, with improved computer availability robots like the LPI-2 with artificial intelligence may reach commercial production. Other expected improvements include increased modularization of robots, increased speed, and durability and reliability with reduced size and costs.

Bulgaria:

Institutions:

Bulgaria is the research coordinator for robotics and applied aspects of automatic machine theory within the Experimental Machine Tool Research Institute (ENIMS) of CEMA.

The producers of Bulgarian robots are the Beroe and Gidrazlika combines, the Sofia Machine Tool Institute, the Plovdiv Technical Design Institute, the Bulgarian Academy of Sciences and the Robotics Research Center of the Sofia Higher Engineering Institute. Additionally, the American firm Versatran collaborates with Bulgarian domestic producers in the production of several robots.

R&D Focuses:

As with other Soviet Bloc countries information about Bulgarian robotics research areas and trends is difficult to obtain. The information available, however, indicates that Bulgarian R&D is mainly concentrated in the area of industrial applications, such as painting and loading/unloading. Additionally, there is some control and AI research carried out at the Robotics Research Center of the Sofia Higher Engineering Institute, while the Beroe combine is the center for the development and commercial production of robots.

Czechoslovakia:

One of the best gauges of robotics research conducted in Czechoslovakia comes from an examination of the Czech robots displayed at the Third International Exhibition of Industrial Robots in Brno, Czechoslovakia. At this exhibition, five Czech robots were displayed, three of which were joint Soviet-Czech developments. All had hydraulic drives, NC control and modular design, hence it can be assumed that Czech R&D, with the apparent help of the Soviets, is at this stage.

Future efforts in Czechoslovakia will be devoted to adaptively controlled robots for assembly, finishing and other applications requiring high speeds, accuracy and reliability. Also, parts transfer robots will be developed for in-process handling of parts up to 160 kg.

East Germany:

Robotics research and development in East Germany is conducted for the most part at the Dresden Technical University's Production Engineering Department, the Cybernetics and Information Institute of the Academy of Sciences and the Fritz Heckert Machine Tool Combine in Karl-Marx-Stradt.

The information available on East German robotics R&D indicates that present research involves the areas of flexible assembly processes for small to medium volume production, tactile sensors and control systems. The research in assembly processes is conducted at the Dresden Technical University and at the Fritz Heckert Machine Tool Combine. Each center has constructed assembly cells for process simulation. The Cybernetics and Information Institute conducts research in tactile sensing and control systems.

Hungary:

Institutions:

Although Hungary does not produce any robot at this time, and conducts little research in the field, an infrastructure exists for Hungarian R&D. Specifically, the Professional Council on Robotics and the Ministry of Industry coordinate development projects, while coordination of robotics applications is the responsibility of Technical Institute of the Machine Industry. There are presently two research centers in Hungary active in robotics research, the Computer and Automation Institute of the Hungarian Academy of Sciences and the Czepel Machine Tool Factory.

R&D Focuses:

The two institutions currently performing robotics research are involved primarily in industrial applications. The work done at the Czepel Machine Tool Factory is conducted with Bulgarian robots coupled with servicing high-precision NC lathes. The development of domestic robots is the responsibility of Microelectronics Enterprise, which is preparing to produce simple

measuring and testing robots. For this goal, \$1.8 million in government aid and an equal amount from Microelectronics Enterprise have been dedicated. Additionally, the Computer and Automation Institute plays a key role not only in Hungary but also throughout the CEMA nations. For example, most of the software for Bulgarian robots was and still is developed at this institute, which is the focal point for coordination of software compatibility throughout CEMA. Finally, the Institute is conducting significant R&D on the application of artificial intelligence in robotics.

Future Directions:

The principle goal of Hungarian robotics R&D is to begin production of simple robots starting in 1985. However, Andras Gabar, Deputy Minister of Industry, indicated that the long term direction of robotic development in Hungary will not be in domestic production of complete robots but rather in joint production with other CEMA nations, in particular, Bulgaria and East Germany.

Poland:

Institutions:

In addition to participating in robotics R&D with other CEMA nations, Poland has its own robotics program involving academic and industrial research centers. Presently, there are two research centers in Poland for robotics. These are the Institute for Biocybernetics and Biomedical Engineering of the Polish Academy of Sciences and the Technical University of Warsaw. At the University of Warsaw there are three separate institutes conducting robotics research.

Industrial research centers have been under the supervision of the Ministry of the Machine Industry since 1970. Those industrial research facilities active in robotics R&D are the Institute of Precision Mechanics, the Machine Tool Research and Construction Center, the Machine Technology and Construction Basic Research and Development Center and the Industrial Institute of Automation and Measurements.

R&D Focuses and Future Directions:

In the near future, specialized robots with few degrees of freedom will be developed; however, in the longer time frame, more versatile modular robots are expected in Poland. One of the areas of future Polish R&D, besides modularization, will be in control systems utilizing microprocessors and simplified programs. Additional efforts are expected to improve accuracy, reliability, arm speed and load capacity.

Yugoslavia:

Institutions:

Yugoslavia, because it is not a member of CEMA, conducts its own independent robotics R&D programs. The predominant robotics research

center in Yugoslavia is the Robotics Department of the Mihailo Pupin Institute. Other institutions active in robotics research include the Jozsef Stefan Institute, the Factory of Hydraulics and Pneumatics, and the Factory of Domestic Equipment.

R&D Focuses:

In the past, Yugoslavian R&D has concentrated on the development of multi-degree of freedom, articulated manipulator systems. These studies have proven fruitful, as evidenced by the number of complex manipulators produced and in use in Yugoslavia. These manipulators are of varying design, using electric, pneumatic, and hydraulic actuators. Presently, research efforts are focused on the integration of microprocessor control with these manipulator systems. Through the import of foreign hardware, such as the Intel 8080 microprocessor, Yugoslavian R&D efforts have been able to concentrate on efficient programming, teaching and control methods for the robots.

3.3. Trends in Robotics R&D

In looking at the vast amount of information concerning research in the field of robotics, one sees that the world-wide R&D effort is not merely a collection of individual, undirected researchers studying various aspects of robotic technology, but that there are several key, unifying aspects of the research effort. With respect to the overall picture, it is apparent that, with essentially only one exception, every country active in robotics research has, to one degree or another, a national direction or program. These programs range from the more coherent, such as Japan's series of national projects or France's country-wide effort to build a manufacturing technology base, to the less structured but still prominent directions, such as the U.K.'s national emphasis on the solution of short-term manufacturing problems. The importance of these programs is that they are the force which directs the thrust of the research efforts. The notable exception to this trend is the United States. Although the amount of robotics research conducted in the U.S. probably exceeds that in any other country, there is no coherent national climate or program directing this work.

A closer study of robotics R&D in the U.S. reveals that, although there is no unified national direction, the individual research funding sources such as the Air Force, the Army, the Navy and other government agencies have their own robotics R&D program goals. These funding agencies, together with private industry, are the forces which determine the direction in which robotics R&D will go. The Air Force, for example, has as the thrust of its robotics R&D program the advancement of aerospace manufacturing technology. This goal is manifest in several different R&D efforts. The first of these efforts, the Advanced Robotic Systems for Aerospace Batch Manufacturing project conducted under the MANTECH program, focuses on off-line programming with CAD/CAM links, drilling/trimming control, and drilling/riveting control, while the second effort, the Intelligent Task Automation (ITA) project conducted under the MANSCIENCE program,

focuses on the study of various aspects of robotic assembly, including sensor and control issues.

In contrast to the Air Force, both Navy and Army R&D programs focus on improving the current capabilities and meeting the short-term needs of each of the services. Maintenance and support are key factors in these programs. Both the Navy's NAVAIR-sponsored wing de-riveter and the Army's DESCOM-sponsored vehicle maintenance project are examples of the emphasis on maintenance. In the area of support, the Army is conducting several studies on battlefield robotics, such as weapons loading/unloading, while the Navy is concentrating on autonomous robots and navigation for undersea work and robotic sentries.

Three other government agencies active in funding robotics research, NASA, NBS, and NSF, each have their own motivations and particular directions. NASA, pursuant to its program goals, is active in funding research in teleoperation and remote sensing in an effort to develop robots for use on a space station. Similarly, NBS is active in performing robotics research in the areas of standardization and system integration. The Automated Manufacturing Research Facility of NBS serves as a testbed for new developments in interface capabilities and system standardization. Additionally, NSF funds, in accordance with its mission, research projects in fundamental issues of robotic technology.

As a final comment on the federal driving forces in U.S. robotics research, it should be noted that, due to the funding policies of the NSF, there is a fair amount of very basic, undirected research conducted at the university level. Occasionally, this research will produce technological progress that in turn will push further research. One of the first examples of this in the robotics field is that of robot vision. Two-dimensional vision capabilities adequate for such applications as simple part identification and inspection were developed in laboratories before there was a significant need for them in industry. As industry slowly began to take advantage of the capabilities, a new push for the refinement and enhancement of these capabilities began.

Industrial robotics R&D has, in general, taken a different direction than that of federally funded R&D. This is due largely to the structure of the robotics industry. Because the robotics industry is in its adolescence, it includes many smaller, very competitive companies. Robot producing companies such as Automatix and Adept Technology have been very active in targeting a particular market, such as vision or arc welding, and focusing their R&D program in a direction to secure that market. Additionally, robot end-users have targeted their R&D programs on application developments that will increase their productivity.

In summary, one can see that there is a vast amount of robotics research being conducted in many different aspects of the field, both within the U.S. and abroad. It is apparent, however, that there are several key research topics that are receiving the greatest effort, both in terms of number of projects and in funding amounts. These topics are presented here as a brief overview of the direction of robotics R&D efforts.

Mechanical:

- o standardized and quick-change grippers
- o sensorized grippers

Control:

- o hardware architecture
- o sensory integration
- o hierarchical control
- o modeling/simulation/emulation
- o high level programming languages

Sensory:

- o processing and interpretation of visual images
- o tactile sensing arrays
- o speech understanding

Although this list shows where the bulk of the current R&D efforts are directed, it is not necessarily comprehensive in the sense that it excludes the category of application-specific development. With the exception of the NSF funded research, almost all of the robotics research performed in the U.S. is driven to some extent by application need. When considering the driving forces behind robotics research, one sees that there are several research topics that are not currently stressed but that might yield substantial pay-offs in terms of increased effectiveness and productivity. These areas include control and structure of compliant manipulators, as well as robust fault tolerance and error recovery algorithms. Additionally, one can see that there is a large amount of effort directed in the field of speech recognition. It is currently under debate whether this capability will be of significant use to industry in the foreseeable future.

4. A Technological Forecast of Robotics

This report has, so far, concentrated on defining the current status of industrial robotics. On the basis of this status, the present chapter describes the development paths that robotics will take in the future. After a brief description of the methodology used to develop the forecasts in this chapter, section 4.2 discusses each component of a robotic system in terms of its current status, developmental needs, approaches to future development, and expected short and long-term results. The last part of section 4.2 takes a broader view and discuss integration of robotic components and integration of the robot as a whole with surrounding equipment. Section 4.3 separates robotic applications into three categories, Low Growth, High Growth, and Blue Sky, according to the effects of emerging technology on each application. The chapter closes, in section 4.4, with the general trends in robotics, with respect to both technology and the robotics industry.

4.1 Methodology

Forecasting technological developments in the field of industrial robotics is difficult because of the rapid change and growth that typifies an adolescent technology. Informed forecasting requires a thorough knowledge of the robotics R&D community and an understanding of the point of view of robot users in industry.

Examination of the robotics R&D community began with an assessment of the technology being worked on in the laboratory. Extensive reading of the recognized journals in the field provided a starting point by indicating the major areas of research activity and identifying many of the key research groups. Attendance at meetings and conferences provided more opportunities to assess current research work and informal discussions with researchers in attendance helped to develop a sense of how the robotics R&D structure operates. Additionally, extensive discussion with the research oriented members of our expert panel provided background information on some of the important research groups, critical assessments of major projects and indications of the directions in which the research groups would like to go.

However, there is another key element involved in making predictions on research: funding. Examination of robotics research included a major effort to identify the funding structure that supports the research. There is very little undirected research funding today; the organizations paying the bills generally have specific problems or at least areas that they want addressed. The funding structure was analyzed not only to locate the major sources and their goals, but also to project future funding levels to allow tentative prediction of the R&D situation in the future.

Information on the robot user point of view was acquired largely from trade journals and interviews with users of industrial robots. These sources provided concrete information on the status of industrial robots

in use today and the developmental needs of end-users. This information was supplemented by discussions with the expert panel which included robot users. In addition, the panel discussions illuminated the role of in-house R&D performed by robot end-users in enhancing current implementation and solving detail problems not considered by other researchers.

4.2. Capability Projection

4.2.1. Mechanical

Manipulator

Current:

Most of today's robot arms are clumsy and slow and generally achieve rigidity (as required for current methods of control) by means of brute strength, i.e., massive components.

Needs:

- Greater speed
- Better flexibility
- Better absolute accuracy
- Better agility
- Better efficiency

New Directions and Approaches:

- Composite materials and more use of tubular cross-section components can achieve rigid but lightweight structures.

- Parallel linkages rather than serial can improve load capacity, and use antagonistic drive to improve precision.

- New types of bearings such as air bearings and ion implanted surfaces can improve joint performance.

- Small, lightweight and precise robots (like the SCARA) can be more suitable for many tasks.

Short Term:

- Rigid but lightweight arm structures will become available, with better payload/robot weight ratios than conventional arm structures. Improved joint and bearing designs will result in reduced friction and stiction, improving precision. Small precise robots for tasks such as assembly will become an increasingly larger part of the robotic population.

- Snakelike manipulators with many degrees of freedom as have been demonstrated for nuclear plant inspection, will come into use primarily for applications where

agility is more important than speed or load handling capacity.

Long Term:

As control problems associated with non-rigidity are solved, robots with light flexible arms will become common.

Non-discrete joints will become available on some industrial robots where agility is important.

Arm development may diverge into two major families:

- o flexible arms
- o parallel linkage arms

with flexible arms dominating light load applications and parallel linkage arms dominating heavy load and high precision applications.

Actuator

Current:

Three types of actuators are currently used in industrial robots, each with some shortcomings:

- o pneumatic - soft operation, difficult to control.
- o hydraulic - messy; precision mechanical components subject to disruption by impurities in fluid supply.
- o conventional electric - low power to weight ratio, adds a lot of weight at the joint, backlash prone, not stiff under load due to reduction gearing.

No currently available actuators incorporate intelligence or control at the actuator to modify actuator response, one promising approach to equalizing arm kinematics over its range of motion.

Needs:

Future actuators will need better efficiency; current arms can typically lift about one tenth of their own weight, with actuator power being one of the major limitations. Less backlash and better stiffness under load will be necessary.

New Directions and Approaches:

Development of direct drive electric actuators is an active area, and addresses many of the problems with conventional electric actuators.

Development of improved pneumatic actuators can result in better control, allowing advantage to be taken

of the desirable aspect of pneumatics, e.g., easy availability of compressed air, high strength to weight ratio, clean operation. Miniaturization while retaining efficiency will be important as interest in micro-manipulation increases.

Modularity of actuators can improve speed of maintenance and speed up design considerably. Moving the actuator off the arm and just transmitting power to the joint can improve arm efficiency.

Incorporation of a dedicated processor for each joint/actuator can allow equalization of the joint kinematics over the entire range of motion.

Short Term:

Improved electric actuators, e.g., rare earth magnets and direct drive, will improve power/weight ratios and precision by eliminating reduction gearing backlash and play.

Some initial versions of tendon drive will appear, although the difficulty of transmitting high torque is likely to restrict this to low power joints such as dexterous hands.

Long Term:

Eventually, reliable tendon drives with high torque transmission capability will become available, used not just for hand drive, but for some of the arm joints.

Distributed actuators, i.e., muscle type with power developed over a volume instead of a line or plane, will be available. The actuator as an integral part of the arm with motion achieved by flexing along the arm length rather than pivoting about a fixed joint will appear for special applications.

End Effector

Current:

Today's common end effectors are crude and inflexible with respect to tasks.

Very few of those in use have any sensing at all, and those that do are limited largely to simple binary tactile sensing.

Because of their lack of versatility, end effectors

generally have to be custom designed and fabricated by the user for each application. Due to the lack of standardization, there is practically no interchangeability among today's end effectors.

Needs:

Versatility is essential, i.e., either end effectors that can handle a wide variety of shapes and sizes or quick change capability allowing the appropriate end effector to be mounted simply and quickly.

Miniaturization, or at least reduced bulk, is needed to reduce interference with surrounding objects during task performance.

Real time sensing at the end effector for adaptive control is needed for many delicate or critical tasks.

New Directions and Approaches:

Standardization of end effectors by performance and interfacing is being actively pursued. Distributed processing for end effector mounted sensors has appeared in the laboratory, but needs much more development work. Varying approaches to dexterity are under development, including but not limited to articulated hands, which can provide a flexibility in task performance well beyond that of any simple gripper.

Short Term:

Quick change capability based on some level of standardization of interface can be reasonably expected in the near term.

Some local sensing at the hand, such as use of an ultrasonic proximity sensor, will be available as a standard part of many off-the-shelf grippers.

Small, coarse tactile arrays will be commercially available but with limited sophistication of processing. Mounting of video cameras on the end effector for part location and identification will become common.

Long Term:

A true general purpose hand, with high resolution force sensing "skin", will become commercially available, providing in a single end effector the capabilities needed to perform the vast majority of applications.

Mobility Mechanisms

This section discusses only the mechanical aspects of locomotion.

Current:

Rail and gantry systems currently provide some mobility for industrial robots, but they are not flexible. They provide only extended reach along one or two fixed axes.

Wheeled systems, while useful in some applications, are restricted to highly structured environments, i.e., smooth floors and a known smooth path. Even then, their ability to precisely locate a tool (or even themselves) is poor.

Needs:

Even operating in an indoor environment, improvements are needed. More precise positioning and repeatability is necessary and whatever drive mechanism is used should be able to traverse a factory floor with moderate level of litter. Once at a destination, if the robot is to be used to perform manipulation, the drive mechanism must be stable enough to act as a fixed base for the robot's manipulator. In addition, mobile robots that mount a manipulator require much better energy efficiency in the manipulator and in their power source.

New Directions and Approaches:

Establishing robot location by sensing fixed beacons rather than using wheel rotation sensors can improve precision.

Legged locomotion systems are under active investigation, but the mechanical and control complexities need a great deal of work.

Much of the development work on mobility systems is aimed at producing teleoperated devices, but this work is directly applicable to mobile robots also.

A number of novel approaches to locomotion are being examined, including hybrid systems that use wheels when suitable and arms to lift or pull the robot over obstacles when needed.

Short Term:

In the near term, mobile robots riding on wheels with some type of supervision will be able to surmount minor irregularities in floors and modest amounts of rubbish without losing orientation or position information. Mechanical registration techniques will be used to allow a mobile robot to position itself

at a work location with precision comparable to that of a fixed robot making a mobile manipulator-equipped robot usable for precision work.

Inspection and simple maintenance required in high hazard areas, such as nuclear power plants, will be performed by robots, with teleoperation capability allowing human supervision.

Long Term:

For highly unstructured environments such as construction sites, active tracked suspensions and legged systems will become available. Robots that can climb by gripping and pulling themselves will be available for work on scaffolds and in outer space.

4.2.2 Control

Current:

Most controllers in use in industrial robots today are primitive by current technological standards. Most operate in an open loop mode, and those that include sensing generally do it in a crude way. Early controllers, due to their limited capacity and versatility were suited to non-sophisticated applications; these are the applications that today show the greatest robotic penetration. In turn, the successful use of simple controllers in these applications has tended to de-emphasize the need for more sophisticated controllers in the minds of many robot users.

Needs:

Controllers need to incorporate more of the currently available computer technology in order to:

- o better integrate sensory data, at much higher speed;
- o have greater capacity to handle complex control problems, such as 6 degree-of-freedom arms with optional path planning and adaptive motion; access data bases;
- o utilize off-line programming techniques; communicate with other machinery and computers.

New Directions and Approaches:

Much of the development work on controllers is aimed towards treating the controller as a computer, and using many of the methods developed to improve the

efficiency of computer systems.

- o Distributed processing

The advantages of this are more than simply load sharing; a satellite processor can be designed for optimal performance for its specific tasks, without requiring general purpose capabilities. Furthermore, the bandwidth required can be greatly reduced because the information being conveyed to the controller can be a sensing result, not all of the sensory data. The development of dedicated special purpose processors is a very active area of R&D.

- o Networking

The way in which various processing modules are logically connected can have an effect on efficiency of the coordinated effort. Additionally, the controller should be able to accept information and commands from above, i.e., a supervisory computer that could incorporate expert systems, AI, etc.

- o Software hierarchy

Software is expected to perform a wide range of tasks, and the level at which tasks are ideally performed is not constant. The development of operating systems for robot controllers will allow task-appropriate access to the computer, from machine language I/O routines and housekeeping modules, canned and ready to run, up to high level language compilers and interpreters that allow the robot to be programmed in an easy-to-use language, with the results automatically converted to efficient execution code prior to use.

Near Term:

Distributed processing, downward from the controller, using dedicated processors connected to sensing systems is likely to become available with vision systems containing outboard processing for image processing and pattern recognition.

When suitable tactile sensor arrays are developed, much of the distributed processing technology for vision may be transferrable to tactile sensing.

Controller processing will become faster and more tolerant of errors as a result of improved

hardware and more sophisticated software. More complex path control will become available, including limited dynamic accommodations, and some optimization of arm trajectory.

Controllers will have software operating systems to handle the housekeeping of distributed processing and to support compilers for high level language programming. Offline programming will be common on sophisticated industrial robots.

Long Term:

Controllers will tie into local area networks to communicate with surrounding machinery such as parts presenters.

Controllers will cease to be directly programmed by humans. AI systems, working from CAM produced information, will use graphics and expert systems, with human supervision, to develop the programs needed by the robot on the plant floor. These programs will be downloaded directly to the controller via an integrated communication network.

As a result of increasing integration, the controller will lose much of its identity as it becomes simply one link in a processing hierarchy, extending from a VLSI chip on the back of a tactile sensor to the top level supervisory computer that oversees the operations of the entire plant.

4.2.3 Sensing:

Vision

Current:

Today's systems are too slow in processing visual data to produce results from vision sensing in real-time and too expensive for many users. Resolution is poor, requiring very prominent features for recognition. Software is neither well developed nor efficient, while depth mapping for 3D is very slow. Lack of standardization makes it difficult to interface vision systems, and standardization is hampered by a lack of consensus on what type of information should be communicated.

Needs:

Vision systems need to become much faster in order to be used effectively, and less expensive to be used

more widely.

New Directions and Approaches:

VLSI chips are being developed for dedicated high speed processors, optimized for this use and separated from the main robot controller. Development of edge imaging and pattern recognition methods to achieve higher speed and better object recognition is very active.

Short Term:

(All in benign environment)

Use of dedicated VLSI processors will speed up 2D and 2 1/2D vision to real-time capability for use in adaptive control.

Range mapping will become faster and provide richer range maps, but real-time 3D vision will take longer to implement than 2D or 2 1/2D.

Better resolution without excessive processing time will allow richer feature sets for better recognition of objects.

Long Term:

Sufficient speed will become available for real-time 3D vision, including shape extraction and comparison with CAD/CAM models.

Increasing sophistication of abstraction and recognition methodologies, applying signal processing techniques, will allow vision to be used in non-controlled environments, with noisy data.

Standards for signal interfacing, using symbolic rather than numeric communication, will finally be adopted, allowing vision systems to be utilized as plug-in modules.

Tactile

Current:

Today's tactile sensors as used in production industrial robots are limited to either simple contact sensing, or force and torque sensing on a single axis. Sensors lack dynamic range and are not very robust.

Needs:

High reliability and long lifetime are essential for industrial applications.

Better resolution in arrays is needed for more precise part location and shape mapping.

Tangential force sensing is needed to detect imminent slippage of gripped parts.

New Directions and Approaches:

VLSI technology incorporating processing and the sensing array itself is being examined to produce monolithic sensor/processing chips.

Exotic sensor materials, such as PVF2, are being sandwiched with wear resistant rubber to produce robust epidermal sensing arrays.

Many of the imaging and pattern recognition methods developed for vision systems are being studied for application to tactile data.

Short Term:

Modest size, modest resolution tactile arrays with dedicated processors, already demonstrated in the lab, will become available on commercial robots, but will not be very common due to performance limitations.

Force sensing along a single axis will become common and multi-axis force sensing will appear on the shop floor.

Long Term:

High resolution wide range force sensing arrays will become available commercially with a sophistication level comparable to that of vision systems.

Sensor arrays with their associated processors in a single package will become available, and standards for interfacing will allow plug-in installation.

Processing of tactile data will become sufficiently improved to allow real-time acquisition of 3D shapes by touching.

Proximity/Ranging

There is very little use of proximity sensing or ranging by industrial robots today. IR sources and detectors are occasionally used to detect obstacles or locate objects, but these are low sophistication implementations.

Ultrasound has been used for coarse location of objects and to detect intrusions into the robot's work volume, but range information is not always reliable and the beam is unfocused, making precise object location difficult.

Eddy current sensing is being explored to locate and

characterize rivets in aircraft but this is a highly specialized application. The complexity of eddy current sensing equipment makes it rather unpromising for large scale general industrial usage.

Laser rangefinding is well developed and is being used for generation of range maps for 3D; it is clearly a workable means of getting range to a point. However, like eddy current sensing, it requires a lot of expensive technology to acquire a simple range, and the possible eye hazards to personnel in the vicinity can be a serious barrier to use in an industrial environment.

A major effect on proximity/ranging development may result from the introduction of the development kit containing the Polaroid ultrasonic ranging system. At a very modest cost, this kit supplies a complete system from transducer to electronics to give range results in an electronically readable form. This system shares the shortcomings of other ultrasonic systems but the easy availability of the kit has triggered a great deal of interest.

Using the kit as a test bed, researchers have demonstrated its utility by mounting it on a variety of grippers to detect gross object location and to aid the gripper in homing in on the object. The near field limitation on ranging has been greatly improved by adding an active damping system to the transducer, and other refinements are likely to appear soon, due in part to the number of researchers now working with the system.

Methods developed for using the Polaroid system and improving it are likely to spawn a new generation of compact inexpensive ultrasonic sensor systems, purpose-built and marketed as easy to use plug in modules.

Sonic

Currently, there is very little use being made of sound sensing for industrial robots. While acoustic signatures have been used to monitor processes such as the seating of snap fit parts, the majority of interest in this area centers on speech recognition for command purposes. This capability is available, but there are three major limitations:

- Vocabulary is limited
- Commands are only recognized when spoken by a single person.
- Recognition is tone sensitive, and becomes unreliable in stressful situations.

It is arguable whether or not speech recognition at this level is a meaningful capability; in the near term it does not seem likely to come close to the flexibility and reliability of keyboard communication.

In the long term, speech recognition will come into its own through the development of artificial intelligence and natural language capability. While someday humans may communicate verbally with high level supervisory computers in the factory, we are not going to see a pick-and-place robot on the shop floor conversing with people.

Smell

Any method of sensing that can produce results in the form of electrical signals can, in principle, be used by robots. While not in use yet, olfactory sensing has the potential for subtle process monitoring. A great deal of preliminary work is needed to identify the chemical emissions of industrial processes and what they imply about the status before any real use can be made of a robotic sense of smell.

4.2.4 Integration

There are two types of integration involved with industrial robots:

- o Internal - coordinating the robot components, especially sensing systems.
- o External - coordinating the robot as a whole with surrounding equipment.

Current:

Internal integration is very difficult unless all components are acquired from the same vendor who also assembles the system. Incorporation of other suppliers' units, such as vision systems, is difficult due largely to the lack of standardization of interfaces and protocols.

External integration is crude. Most current industrial robots operate as an "island of robotics", and connect with surrounding equipment via parts feeders and fixturing. While CAD/CAM databases often coexist with industrial robots, no one at this time has implemented direct communication and coordination.

Short Term:

Internal integration will improve as communication and interfacing standards develop. Sensing systems will be the first well modularized components, allowing

selection of any one of a variety of vision systems for a particular robot.

External integration will reduce the robot's dependence on expensive and inflexible fixturing and feeders. They will be replaced by simpler mechanical systems as robots become more flexible and less demanding on peripheral equipment. Some of the burden of parts presentation will be taken over by simple robots, such as mobile carts and pick-and-place robots. Coordination with external computer systems such as graphic modelling systems will become common for sophisticated installations.

Long Term:

Internal integration will be greatly improved by industry-wide standards for interconnection. A buyer will be able to add to or upgrade his robot's capabilities by plugging in modules for control or sensing functions. This will also result in reduced down time for robots by allowing rapid replacement of failed modules to bring the robot back into production.

External integration will connect and coordinate entire production lines, including many robots. CAD/CAM Systems will connect with graphics aided robot programming systems which will then download the resulting programs to the robot production line. Each of these systems will keep a high level supervisory system informed of progress of all projects. This supervisory system will perform the necessary planning, stock and machine allocation, maintain inventory and maintenance schedules, and support a sophisticated Management Information System that provides any requested information about any section or level of the entire system.

4.3 Application Projections

With respect to the effect of future developments in robotics, there are three major categories of robotic applications:

Low Growth Applications - Developments in robotic technology will not produce sweeping increases in robotic penetration.

High Growth Applications - As developments in the laboratory and development stage become commercially available in the near term, these applications will show very rapid increases in robotic penetration.

Blue Sky Applications - These applications require capabilities that are still in early developmental stages. Robotic penetration will be very slow starting, and will not become significant in the near term future.

Low Growth Applications

Robots in these applications are generally characterized by:

- binary sensing
- programming by lead-through or walk-through
- preprogrammed unvarying path
- operation in very structured environment
- no use of knowledge or internal models.

These applications are currently well penetrated by robotics, and today's robots perform well. Primary barrier to further robotic penetration is cost of the robot and cost of set-up for a task, i.e., large batches are needed.

Spot Welding -

- o requires that a tool be moved to a point and squeezed
- o is being performed successfully open loop, with no adaptive control
- o no great interest in more technical sophistication
- o shows high penetration (mostly in automotive), but has reached a plateau
- o requires large batches to be economical due to the high cost of the robot and clumsy programming

Spray Painting and Coating -

- o requires that a spray gun be moved along a smooth path while triggering the spray
- o is being done successfully open loop
- o could be enhanced by sensing, but there seems to be little interest in this among users
- o shows good penetration (mostly in the automotive industry)
- o requires large batches for economical use due to the very high cost of painting robots

Forging -

- o requires that a hot work piece be placed in a die, and removed after forging
- o is commonly done by pick-and-place robots
- o shows some use of IR sensing for verifying that the work piece is gripped
- o uses the robot as a peripheral device; robots won't bring about major changes in forging

Investment Casting -

- o requires that a form be dipped in slurry and dried (repeatedly) to build up a mold
- o is being done open loop
- o produces consistent molds - the key to successful investment casting
- o shows modest penetration that will increase steadily but not going to be overwhelming
- o much investment casting done by small jobbers in small shops, limiting penetration due to cost

Sealant/Adhesive Application -

- o requires that an applicator gun be moved along a preprogrammed path
- o can be performed with no sensing but can leave voids undetected
- o simple vision allows void detection and repair
- o is time critical since work time for hot melt or epoxy adhesives is short
- o reduces waste; more consistent bead gives higher quality bond or seal
- o is an increasingly popular way of joining parts because it is cheaper than mechanical fasteners
- o robotic implementation is growing because of growth of process and robots work well in unpleasant, low paid job

Die Casting -

- o robots are used to eject casting and to clean and lubricate dies
- o with minimal sensing, the robot detects remnants in the die, and cleans the die only when necessary
- o major effect on casting process is prolonged die life due to consistent lubrication

High Growth Applications

Robots performing in these applications will be generally characterized by:

- vision up to 3D
- force and torque sensing
- force sensing arrays
- adaptive control of path and process
- off-line programming capability
- enough adaptability to operate in less structured environment than low sophistication robots
- use of knowledge and simple internal models.

These applications are lightly penetrated by robots today. There are major technical barriers to further penetration such as limited sensing capability, insufficient speed, inadequate precision or dexterity and inadequate adaptability to variations in task.

(In this section, open bullets indicate the use of currently in place technology while solid bullets indicate technology and capabilities expected to be available in the near future.)

Material Handling -

- o simple pick-and-place
 - is being performed with minimal or no sensing
 - requires parts presentation with precise location and orientation; this can result in large fixturing costs
 - functions very efficiently as interfaces between robot cells, and as integration of production lines improves,

demand will increase

- o parts acquisition with 2D vision

- has been used to acquire and orient parts from a parts table
- is beginning to be able to handle overlapping parts, but requires a controlled environment e.g., backlit table
- reduces the demands of parts presentation but is still short of bin-picking
- this level of implementation will remain in use even when real time 3D vision becomes available for reasons of simplicity and cost

- parts acquisition from jumbled pile

- this is an active research area
- solution to bin picking in a commercially available form seems to be imminent
- eliminates most of the cost of external parts presentation equipment
- allows use of robots in industries that normally store parts in bins
- will enhance robotic assembly by reducing peripheral equipment requirements
- may see major application as first robot in integrated manufacturing lines, feeding new materials from unstructured storage.

Arc Welding -

- o open loop, non-adaptive

- simply moves torch along smooth but fixed path
- requires fit-up and fixturing at a quality level that is unrealistic for most industries
- this level of implementation is fading as adaptive path control (seam tracking) becomes common

- o adaptive path control

- once started on a seam, the torch follows the actual seam, compensating automatically for small errors
- most of today's systems perform in two passes, first to locate and memorize the seam with the actual welding performed on the second pass
- one pass systems, sensing during welding, are becoming available, and are faster than two pass systems
- through-the-arc sensing not only allows seam tracking, but also limited process monitoring
- these systems cannot do a good job of accommodating wide gaps along the seam either by adding more filler material or by rejecting the assembly as unweldable

- adaptive process control

- weld parameters are monitored during welding with either through-the-arc sensing or vision systems that watch the size and shape of the weld puddle
- this sensing allows process parameters to be controlled to compensate for poor fit-up and variability of materials
- improves the success rate on thin materials and difficult welds, e.g., thin pieces to thick pieces
- reduces the amount of effort needed to prepare the assembly for welding

Routing, Drilling and Grinding -

All three of these processes are force critical rather than position or speed critical, i.e., the parameter to be controlled is force or torque.

- o open loop, no force or torque sensing

- In order to prevent excessive forces or torques from developing, feed rates must be kept very low, resulting in very slow processing.

- o adaptive feed control with force or torque sensing

- Each of these processes involves bringing a rotating cutter against the work piece while moving the entire tool along or into the work piece.
- The process can be monitored by sensing torque required to drive the rotating cutter, or by sensing the force

required to move the tool along its path; both approaches have been used.

- While the cutting process can be controlled, where the cutting is done remains a problem in terms of positioning accuracy, and allowance (especially in grinding) for tool wear.
- To achieve high precision in drilling and routing today, precise templates are used to bring the tool to the work at the precise location desired.
- Templates are expensive to make and use, and generally a different template is required for each type of workpiece to be handled.
- Even with cost of templates, robotic drilling is becoming increasingly popular in aerospace for drilling rivet holes in skin sections because of the requirement for a large number of precisely located and drilled holes.
- Robotic grinding today is generally used for non-precision applications such as grinding flash off of castings.

- real time sensing

- Tactile or proximity sensing can be used to locate registration features on jigs, improving the precision of tool location without templates.
- Real time sensing of arm deviation from expected path when under load will make precision drilling and routing possible without templates, giving a large boost to aircraft skin applications.
- Eliminating the cost of templates will reduce the batch size required to justify a robot, making it attractive to a wider range of users.

Inspection -

- Inspection is being done with simple vision systems and proximity sensing.
 - Limited resolution and speed restrict inspection to, in general, verifying that a part is in place.
 - Similarly, inspection robots can easily verify that the workpiece has a hole in it, but verification of the diameter or location of the hole with high precision requires sophisticated and complex computation.
 - Surface texture inspection is not usable today; today's

inspection systems cannot distinguish between a scratch and a crack in a surface.

Improved robotic inspection is going to result from two approaches: improved robot performance and transplantation of existing non-robotic inspection technology.

- improved robotic performance

- High precision positioning over all of the robot's work volume will allow tactile inspection by mapping surfaces through feel; this has already been suggested as a method of inspecting aircraft structural components containing fillets, webs and cut-outs.
- The resolution of vision systems determines how small a detail the inspection can detect; as vision resolution improves, texture inspection will become more feasible.

- transplanted technology

- Currently available Non-destructive Evaluation (NDE) techniques, using the robot as a positioner and interpreter, are under development now.
- X-ray examination can make use of robots to speed up the process by positioning heavy x-ray equipment more rapidly than humans. Removal of the human operator also allows the use of higher radiation levels, improving resolution and penetration.
- Eddy-current measurements currently being investigated for locating rivets in airframe components can be refined and used for detection of deep flaws.
- High sensitivity magnetic sensors or sensor arrays will allow an inspection robot to map the magnetic field at a surface with an applied external field. Surface defects distort the magnetic field and appear as anomalies in the surface field map.

Assembly -

- Easy mating assembly is being done with minimal sensing as a special case of material handling, where the part is simply moved to the final assembled position. This approach is used for high clearance, compliant parts.
- closely fitted assembly

Today's implementations are seriously restricted by technological limitations:

- Sufficient precision in part positioning prior to insertion is not currently available; compensation for this is either by use of Remote Centers of Compliance (RCC's) or search algorithms that are slow to execute.
- Chamfering, which requires a change in parts fabrication, is generally needed.
- Most successful implementations involve radially symmetric parts assembled on a shaft, such as washers, sleeves and bearings slipped onto a motor shaft.
- Jamming is far too common due to lack of adaptive control for final positioning; as a result, parts are frequently damaged and the assembly process disrupted.
- Insufficient error detection prevents flawed assemblies from being detected prior to subsequent operations.

In spite of these difficulties, assembly is showing some robotic penetration in suitable labor intensive, high volume applications, and interest in improvements is very high.

- Developments in the near future, such as:

- improved mechanical precision
- vision to guide robot to the hole more precisely
- bin picking to make parts presentation more economical
- improved insertion algorithms to reduce jamming and speed the process
- error recovery routines to keep robot working will make robots much more attractive for assembly applications, and by replacing skilled (i.e., expensive) labor, will improve the economics of robotic assembly. Due to the combination of large volume production and pre-existing familiarity with robots, the automotive industry is likely to be an early user of robotic assembly.

- micro-assembly

- requires high precision while operating at a very small scale
- necessary miniaturization is not going to be available in the near future
- interest is high in the electronics industry; electronics will remain a high growth industry, and by the time miniaturization is available, the industry will be well

acquainted with the use of assembly robots at the printed circuit board level

- as soon as the technology is available, this application will grow very rapidly.

Blue Sky Applications

Robot that will perform these tasks will require combinations of the following characteristics:

- autonomy
- mobility
- expert systems
- artificial intelligence

These applications have no current robotic penetration. The demands that they make on adaptability, decision making and mobility are not available in today's technology. Furthermore, unlike the barriers in the previous section, work on the capabilities required for these applications is still in the preliminary stages of development.

In the near future, the work that will be done that relates to these applications will be based on teleoperated machines. This allows a human operator to fill the need for intelligence and decision making, the robot attributes that are the farthest from commercial availability. As a result, much of the development and engineering required for intelligent autonomous robots will be available as soon as AI capability becomes available.

Nuclear Plant Maintenance

Inspection and maintenance in the radioactive areas of nuclear power plants is generating a great deal of R&D effort, especially in France and Japan. Most current work is focused on the development of teleoperated inspection devices, but the ultimate goal is the development of mobile equipment capable of performing any needed repairs in the high radiation areas of the plant. Such equipment will require a high level of mobility to navigate in a cluttered environment and the ability to reach almost inaccessible areas. Performance of repairs will require the appropriate tooling for replacing tubing segments and re-welding seams. Inspection and certification of repairs will also be required.

An autonomous robotic system to perform these tasks may eventually be developed, but teleoperation capability will be retained to provide a back-up control system. Indeed, once the difficulties involved in performing these tasks via teleoperated devices have been solved, the need for the next step, development of an autonomous robot for this role, may not be very pressing. For regulatory reasons, the

level of human monitoring in these plants is likely to remain high. In addition, the detail differences from plant to plant, and the complexity of diagnosing and repairing unpredictable failures, are likely to result in a teleoperated solution being accepted as the final result.

Housekeeping

Cultural biases notwithstanding, housekeeping encompasses a great variety of complex tasks involving judgmental decisions at almost every step. These tasks must be performed in a very unstructured environment, subject to frequent rearrangement. In a home, the proximity of children and pets requires careful attention to safety factors.

A truly sophisticated housekeeping robot, able to accomplish the entire range of household chores, will tax AI capabilities to the limit, and will not be commercially for a long time. However, a robot with a limited task repertoire, such as carpet vacuuming, could be marketed in the foreseeable future. While it might not be cost-effective in the average home, this does not mean it would not sell; Americans have historically had a love of gadgetry. Additionally, the increasing number of elderly in our population can provide a ready market for robots to perform simple but tiring chores, provided that the human/machine interface can be simple and non-threatening. Such a robot could open up the home market, and generate strong demand for more sophisticated home robots in a shorter time frame than might otherwise be expected.

Construction Labor

This is personnel intensive work that will be very difficult to robotize because of demands of the construction environment. Mobility problems, both mechanical and control, are a major barrier for this application. A robot in this application may have to transport itself and its load over uneven, some times muddy terrain, climb ramps and scaffolding.

In addition to the difficult terrain, construction sites are inherently changeable environments, both in terms of progress on the structure and in terms of large amounts of material temporarily stored in arbitrary locations. Mechanical reliability of complex locomotion systems in an environment loaded with dust, grit and dirt is a problem requiring a great deal of work.

Interest in construction robots will be driven by economic considerations. Not only are serious accidents expensive, but development of chronic and disabling conditions as a result of the physical strain of the work must be considered in the cost of labor. Current practice of paying modest hourly rates with no fringe benefits for laborers will have an increasingly difficult time in attracting sufficient manpower; the result is likely to be major increases in the cost of keeping personnel on site.

What is likely to appear before robotic construction site laborers, is the use of robots for off-site construction tasks. Much of the construction performed today consists of joining prefabricated units. This moves much of the labor of construction back from the building site to a factory, an environment that is much easier to robotize.

Maintenance by Expert Systems

The maintenance and repair of mechanical systems is very labor intensive and requires a high level of expertise when performed by humans. There are indications that the automotive industry may lead the way in this type of application. Several years ago, Volkswagen introduced a diagnostic system for some of their models, in which an automatic electronic diagnostician was plugged into a specially designed connector built into the car. This idea was apparently premature, and faded from sight. However, the increased use of electronic controllers for automobile engines, and the rising use of electronics in automotive instrumentation indicate that an automated diagnostic systems may not be far in the future. With expert system capability, the automated diagnostician could guide a human helper through the needed repairs and adjustments step by step, reducing the need for skilled human labor.

One can foresee more ambitious robotic applications in automotive maintenance, considering the number of automobile parts that are commonly rebuilt. These range from carburetors and alternators up to automatic transmissions. In the future, robotic systems will combine the precision and dexterity developed for assembly operations with inspection capability. With the addition of an expert system that can recognize parts needing replacement, a robot could perform the entire task, requiring only the old unit and a kit of replacement parts. This application may be nearer in the future than many others in this section since the rebuilding business is already somewhat concentrated, and trading in worn-out units to replace them with rebuilt units is a well established practice.

Hazardous Environment Rescue

Fire fighting frequently involves entry to burning structures to locate trapped people and transport fire fighting and support equipment. The number of firemen killed each year in the line of duty is a clear indication of the level of risk involved. Due to the direct reduction of high risk to humans, the economics of this application will have less effect than the high demands on mobility and autonomy. For rescue purposes, the robot must be able to select a path through a cluttered and rapidly changing environment, recognizing and assessing severity of thermal hazards. For delivery of equipment, (hoses, air bottles, etc.), the robot must also be able to find the destination where the equipment is needed. AI will be essential for risk assessment: a path that is likely to result in the destruction of the robot would not normally be selected, but a path with a high

probability of destroying the robot may be acceptable when human life is at stake.

Orbital Construction

The high cost of labor has been a strong incentive to use robots in many applications, and the cost per man-hour of work performed in earth orbit may be the highest of any human endeavor. A major part of this cost is for transportation of the astronaut and life support equipment, and, due to the limited time that humans spend in orbit, this is a frequently recurring cost. Unlike a human, a robot needs to be transported only once, and only one way, while the required support equipment is only a fraction of that needed for a human. As a result, the cost of orbital construction may be significantly reduced by the use of robots.

If the development of space continues and grows as expected, orbital construction will become increasingly important. Space structures will be assembled from pre-fabricated components and can be designed for robotic assembly.

Some of the problem areas for this application are:

- o establishing location - Sensing of active beacons seems feasible, though the work site is likely to be cluttered, requiring redundancy.
- o motion control - Zero-g maneuvering is a complex problem, though much has been done in developing maneuvering systems for untethered operations from the Space shuttle.
- o environmental protection - Methods to protect sensitive electronic and mechanical components from the orbital environment (vacuum, radiation) are not simple, but have been developed for the space program.
- o system integration - Coordination of a robotic assembly crew is much more complex than coordination of several industrial robots. Mobility in three dimensions and the level of autonomy in each robot are two major sources of the additional complications.
- o compensation for reaction forces - In a zero-g environment, application of force to a tool or workpiece requires that the worker be solidly anchored to avoid being moved out of position by the reaction force. This problem has become apparent for shuttle personnel working in orbit, and solutions to the problem are being developed. A robot is going to need an anchor point at each work station (which can be incorporated in the component design stage) and a way to attach itself. An alternative to mechanical anchoring to deal with rotational reactions is the use of counter rotating flywheels. Translational reaction forces would still require compensation with gas jets, using up fuel, but the elimination of the

complexities of mechanical anchoring might make this the preferred way to go; it is too early to tell.

Based on the above discussion, we can summarize these three groups of applications in terms of their current levels of implementation and the effects of emerging technology on their future direction.

Low growth applications are those in which current robotic capabilities are well matched to the application requirements. The robots in these applications perform satisfactorily with little or no sensing capability. Advances in sensing systems that will be appearing in the near future can extend their capabilities somewhat, but will produce refinement rather than qualitative change. Programming methods used are generally walk-through or lead-through today, but incorporation of off-line programming, if the needed accuracy can be incorporated, will make their implementation easier but will not change their fundamental capabilities. Today these robots usually operate as "islands of automation"; in the future they will be more closely integrated with surrounding machinery. They are demanding of their environment, requiring rigidly structured and undeviating surroundings.

The net effect of developments in robotics on these machines will be to make them more flexible, easier to program and less demanding of their environment, all of which reduce costs. This will result in lowering the batch size that is economical to process robotically, but will not fundamentally change the current situation. While penetration with respect to the application will rise steadily, robots in these applications as a percentage of all robots will fall as robots in medium sophistication applications become more widespread.

The category of high growth applications will show the strongest growth over the next 2 to 6 years. Today's limited implementations have demonstrated feasibility, and limitations are clearly identifiable. Furthermore, possible solutions to today's technical barriers are already in the laboratory. The barriers in these applications are predominantly in sensing and sensory integration, and as has been described above, major advances and improvements are expected in these areas in the near term.

Two key aspects of these applications that indicate the likelihood of rapid growth are that the barriers are susceptible to solution by development of current laboratory technology and that they are personnel intensive processes. The first will make robotization possible, the second will make robotization attractive.

Blue Sky applications are those that are not likely to utilize robots for quite some time. The key element in each of them is the ability to perform tasks autonomously. While current sensing techniques may not be adequate for these applications, the major barrier to implementation is the lack of Artificial Intelligence in a robot. Since work on AI is still in an early stage, predictions about its

development are difficult. Furthermore, in the time frame in which AI can be expected to develop sufficiently for these applications, the strength of motivation for implementing robots for these tasks may change considerably. As an example, for construction work, today's primary motivation would be economy since human labor is expensive and likely to become more so. Economic changes that would drive the cost of labor up sharply would accelerate interest in this robotic application, while a depression that drove the cost of labor down sharply would reduce interest.

4.4. General Trends

4.4.1. Trends in Robotic Technology

The general trends we expect to see are:

- o Separation of high sophistication robots from simple robots:

Simple specialized robots for suitable applications, such as pick and place and assisting sophisticated robots, will become smaller, less expensive and better integrated with adjacent equipment. They will be recognized as having an important role to play, not thought of as just a second rate version of a sophisticated robot.

Sophisticated robots will be much faster and more flexible, able to handle a greater variety of tasks and capable of dealing with more deviation from expectation in performing a task.

- o Sensing will become both faster and better, and integration of sensory information will be much more efficient.
- o Mobility will be easily available due to improved mechanical mobility systems, more energy efficient design, and better self contained power sources. Improved sensing will provide precise location information and navigation methods will allow flexible path selection and optimization.
- o Future robots will take advantage of lighter materials and more efficient design, and the lightweight, composite material arm may replace today's massive metal castings in heavy duty industrial arms.
- o Perhaps the greatest change will be the extent of robot integration. Sophisticated robots will communicate downwards to dedicated satellite processors, sideways to adjacent robots, and upwards to supervisory control

systems.

- o Robotic work stations in which sensor mediated manipulation and inspection are being developed for specific tasks in a fully automated production line. While very expensive to develop, the ability to market the basic system to a variety of customers with only minor changes will make this a cost-effective route for development, and tend to produce, indirectly, a certain level of standardization.
- o Lower cost is going to be a major trend in both sophisticated and simple robots. Some of the cost reduction will result from improved technology, either providing capabilities at lower cost, or providing more capabilities at the same cost. Another major factor in cost reduction will be economics of scale as the increasing number of robots being manufactured moves robot manufacturing more into mass production.
- o Modularization will become well developed, as interface standards become accepted, allowing robots to be purchased in much the way a car is purchased: a basic model with a buyer specified list of options. Additionally, this modularization will improve the situation for third party component integration.
- o Higher volume production and improved standardization will bring robots closer to being off-the-shelf items. This will reduce lead time when ordering, and increase confidence levels that subsequent robots will match the performance and specifications of the first ordered.
- o Hybrid robotic/teleoperated devices will become common, leading the way in applications that will eventually be handled by fully autonomous robots, with teleoperation serving only as a fall-back method of control.

4.4.2 Trends in the Robotics Industry

At present, the number of companies in the U.S. producing and marketing robots or robot components is quite high, more than today's market can support. A shakeout is occurring, and many of these companies are likely to disappear. Small, undercapitalized companies are at greatest risk, but larger companies are not immune from the pinch. Note that Copperweld has recently dropped their robotics product line. Small companies are severely hampered by the industry-wide lack of standardization; an excellent vision system that is difficult or impossible to integrate with commercially available arms is not going to be easy to market. Conversely, controllers that cannot easily integrate external inputs will become increasingly more difficult to market.

Indications of the state of flux in the industry can be seen in the Westinghouse/Unimation situation. In a relatively short period, Unimation split into Unimation-West and Unimation-East, Unimation-West became Adept Technology while Unimation-East was bought by Westinghouse.

During the next several years, the robotics industry is likely to be in a state of flux; however, some trends seem likely to appear:

Many of the larger firms will be marketing Flexible Manufacturing Systems, and robots as components of FMS.

More companies will market robots to Original Equipment Manufacturers (OEM's), who will use the robot as the basis of a retail product, adding features and customization.

Suppliers of complete turnkey systems will become more prominent, offering completely integrated and supported systems, minimizing the hidden costs of a robot.

Greater product differentiation and market segmentation will develop as vendors try to carve out either application specific or component specific markets. The first of these can be seen today in the way that DeVilbiss has established itself in the field of spray painting robots; the second is currently hampered by lack of interfacing standards.

Robot leasing and rental companies may become more prominent, in a way similar to current practice for main-frame computer systems. This will allow companies to begin using robotics with a much smaller initial investment, and will, to some extent, protect the user from being burdened with obsolete equipment.

The introduction of large numbers of inexpensive hobby robots will create a large pool of people working in robotics. This will bring a great deal of ingenuity to bear on some of the problems in robotics, and may become a major force in technological innovation, much like the effect that amateur radio operators have had on radio technology.

5. Conclusion

In consideration of the scope of this report, from a detailed analysis of the current status of robotic technology to a forecast of the future of robotics, this report is best concluded by giving the reader an understanding of the key interplays that connect R&D, the level of available technology and robotic applications. This chapter is divided into two parts, Dynamics of Technological Innovation, which describes the way in which research affects the level of available technology, and Evolution of Robotic Application, which illustrates the way in which available technology determines robotic applications.

Dynamics of Technological Innovation

The capabilities of industrial robots have progressed from the early industrial robots that could do little more than pick-and-place applications, but this progression has consisted of surge and consolidation stages, rather than steady development. From the introduction of industrial robots on the shop floor in the early 60's through the late 70's, industrial robots acquired continuous path control, better repeatability and improved reliability. However, the result of these improvements was to enhance robot suitability for the early applications such as material handling and spot welding, rather than to extend robot utilization to new and more demanding applications.

Meanwhile, a university oriented robotics R&D community was beginning to take shape as robotics began to be seen as an interesting and potentially high growth area of funded research. While the capabilities required in a robot for the early applications were considered a solved problem, it was clear that many other industrial processes would require sensory and control capabilities well beyond those available from contemporary robots. Furthermore, many of the new entrants into robotics R&D came from areas such as computer science, prosthetics and control theory, and brought with them more of a basic, long term research orientation, in addition to infusing robotics with technology from the other fields. The results of these R&D efforts have been appearing since the late 70's as a second surge in the capabilities of robots on the plant floor.

The robots of this second surge differ from the earlier robots in two main areas: sensing and control. Vision systems are common on these second surge robots, typically 2D or 2-1/2 D. Robots without vision are likely to have force or torque sensing. Both types of sensing are used to provide the robot with information about its task, and with sensory integration provided by the controller, allows the robot to modify its actions to suit the situation, i.e., adaptive control.

With these capabilities, industrial robots have started to penetrate more demanding applications, with arc welding being the most prominent today. However, the application that many believe will dominate industrial robotics by the late 80's is assembly. Penetration of robots into this field is just beginning, but the potential market is tremendous, and robots designed explicitly for assembly tasks are becoming available.

Another important characteristic that will be seen as the robots of the second surge are installed is extended integration. The use of industrial robots as "islands of automation" is going to be supplanted by Flexible Manufacturing Systems, which integrate and coordinate an entire production line of robotic and automated work cells. This approach to implementing robots reflects a fundamental change in philosophy. The "island of automation" idea was based on the view that a robot is a replacement for a human worker, and this was the basis for most implementations of first surge industrial robots. Implementations of the second surge industrial robots will reflect the more subtle view of a robot as a production tool, one part of a production system.

While there is still a great deal of work to be done on robotic sensing and control, it appears that the basic elements that will drive a third surge in industrial robots are now in the early developmental stages in the laboratory. In a way similar to that in which second surge robots moved into applications characterized by the need for sensing, the third surge will carry robots into applications characterized by the need for autonomous action.

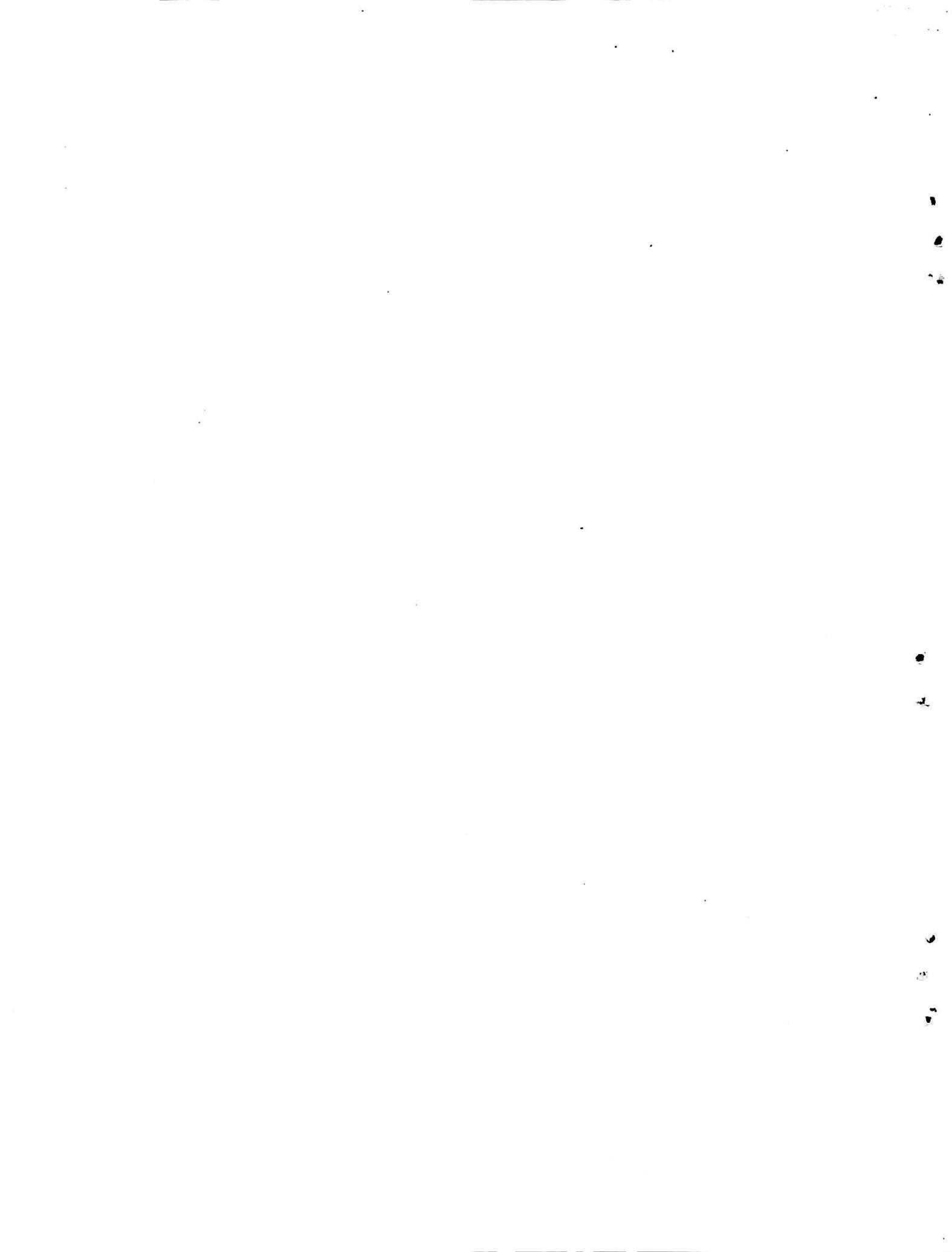
Evolution of Robotic Application

The early robots were typically capable of moving an end effector to specific, repeatable locations, and with the advent of continuous path control, could perform the intervening motion over a smooth, controlled path. Unloading die casting machines (a specific type of material handling), spot welding and paint spraying were all tasks within these capabilities and were early applications of robots. These applications set the pattern for the first wave of industrial robots: simple robots performing simple tasks. With an early start and a history of successful implementations, these applications showed a rapid growth of robotic penetration through the end of the 70's. Today, these are the most heavily penetrated applications, but the growth in penetration has levelled off. Technological developments expected in the near term will not open up significantly larger markets for robots in these applications, and the percentage of robots in these applications versus all industrial robots in use will decline as more demanding applications such as arc welding and assembly become robotized.

The beginning of the second wave of robot penetration can be seen today, with arc welding being the prime example. This second wave will be characterized by robots with greatly enhanced sensory capabilities, as compared with the minimal sensing typical of the first wave robots; this increased sensing is required by the applications in which these robots will be used. Arc welding is showing a significant amount of penetration today, using sensing and control technology that have only recently become available. The quality of sensing available today is also sufficient for initial implementations of robotic assembly, but developments that are now on the way from the laboratory to the shop floor are going to dramatically enlarge the potential market for robots in these applications. As a result, the penetration of second wave robots is going to grow rapidly in the near future and these robots, especially in assembly applications, will eclipse the first wave robots, and become the dominant portion of

the robotic population. Along with improved sensory capability and control, the robots of the second wave are going to be better integrated with surrounding equipment, including other robots. The logical extension of this integration is the Flexible Manufacturing System (FMS) in which an entire production line of robots and automated machine tools are integrated and coordinated by a supervisory computer system. Such systems have been assembled today; the major change expected in the near future is greater ease of integration due to industrial robots being designed with integration capabilities from the start.

How the third wave of robotic penetration will come about is not clear, but areas in which long term research is now being performed give some indications of what can be expected. The key to the third wave will be the incorporation of Artificial Intelligence into robotic systems. In the same way that the second wave robots opened up entirely new applications for robots, the third wave robots will extend robotic capabilities into yet another level of applications. Maintenance and repair performed by expert systems is being examined by the Army as a means of reducing personnel requirements, especially under battlefield conditions. Autonomous robots for construction in outer space is likely to be another third wave application. The thrust of third wave robotics will, when it appears, be the replacement of highly skilled humans with robots.



Appendix A

CURRENT APPLICATIONS

Section 2.3 of this report summarized state-of-practice applications of robots in industry. This appendix is supplied for the reader who is interested in a greater level of detail than presented in the body of the report. The successful performance of many manufacturing tasks requires process considerations that may not be obvious to a reader without considerable exposure to the specific application. Similarly, the implementation of robotic systems in the industrial arena can give rise to difficulties with and limitations of current robotic products that are unfamiliar to a person whose background is not in robotics.

This appendix highlights aspects of the intersection of manufacturing technology and robotic technology. It is not intended to be definitive, and readers interested in greater detail than provided by this appendix are referred to the Bibliography (Appendix D) included in this report.

This appendix is divided into sections by specific application areas, starting with what are termed, for the purposes of this appendix, major applications, followed by minor applications. Any application in which robotic technology is very prominent is considered a major application, regardless of the level of robotic sophistication. In the major application area of welding, resistance (or spot) welding is an example of a relatively undemanding robot application that is prominent due to the high level of penetration of robots. The very simplicity of the application resulted in early and successful robotization of the process and predictable equipment investment paybacks. On the other hand, a sophisticated and demanding application in which there is a great deal of industrial interest, such as robotic assembly, is considered major even though robot penetration is not large at this time.

Application areas that are primarily extensions, special cases, or combinations of major applications are considered in this appendix as minor applications. They are presented in less detail, with referrals to the appropriate major application sections.

Each application section is organized in six parts: (1) Process Description, (2) Process Considerations, (3) Basic Elements, (4) Justifications, (5) Current Technological Constraints and (6) Application Examples. The first two parts deal with the generic process, the next three parts deal with robotic implications for the process, and the last part illustrates approaches that have been used to robotize the application.

Process Description: This section briefly describes the fundamental steps required for the specific industrial process. The steps are presented in sequential order reflecting manufacturing practice.

Process Considerations: This section points out aspects of the process that are either crucial to satisfactory performance of the task or that make performance of the task particularly difficult.

Basic Elements: This section describes the generic robotic components that are in use in this particular application. It is often seen that the same process can be implemented at various levels of sophistication, especially with respect to robot sensing systems.

Justification: This section points out the aspects of the application that tend to favor a robot over a human worker.

Current Technological Constraints: While all of the applications described in this appendix have been implemented, robotic penetration remains limited. This section identifies, for each application, some of the limitations in current robotic technology that prevent deeper penetration by robots into the application.

Application Examples: For each application, this section briefly describes specific implementations of robots, noting which Basic Elements are used, and illustrating various approaches to the points raised in the Process Considerations sections.

1. Welding

There are two major processes in use in industrial welding: resistance (or spot) welding and arc welding. Although the two processes are very different, we have followed standard practice by including them under the major category of Welding. The emphasis in the following analysis is on arc welding because, of the two processes, it is the more demanding, and has shown less penetration by robots than spot welding.

Process Description

Arc Welding

- o align parts to be welded
- o heat parts at seam by generating an arc between welding electrode and work pieces
- o apply filler material as needed
- o monitor weld for bead width, penetration depth, seam filling

Spot Welding

- o align pieces to be joined
- o clamp pieces between welding electrodes
- o heat pieces at weldpoint by passing a high current between welding electrodes.

Process Considerations

Parts alignment is vital to satisfactory performance in both types of welding. The two aspects of parts alignment can be characterized as set-up (how are the parts to be joined positioned relative to each other), and seam alignment (how well are the surfaces or edges to be joined aligned with each other). Both of these aspects are established by the fixturing

used to hold the parts and the dimensional correctness of these parts. Set-up determines if the unit as a whole will be acceptable and is not affected by the actual welding operation. Seam alignment affects the welding operation by dictating the amount of filler material required. If the seam alignment is very poor, an acceptable weld may be impossible. Figure A-1 illustrates the two aspects of parts alignment. Example b in this figure illustrates poor set-up due to improper fixturing; while the seam could be welded, the finished unit would be unacceptable. Example c shows good set-up but poor seam alignment as a result of a bad edge on the horizontal piece. The poor seam alignment illustrated in example c is a common occurrence when welding heat treated parts due to dimensional changes and warpage caused by heat treating.

In addition to positioning the work pieces correctly with respect to each other, positioning of the welding tool with respect to the work pieces is also critical for successful welding. For spot welding, the electrodes must be brought together from each side of the work pieces, aligned with each other and perpendicular to the surfaces of the workpieces. If the work pieces are deeply contoured, access to the inner side of the weld can be difficult, while large work pieces require a long, precise reach to bring the welding electrodes together at a point far from the perimeter of the workpieces.

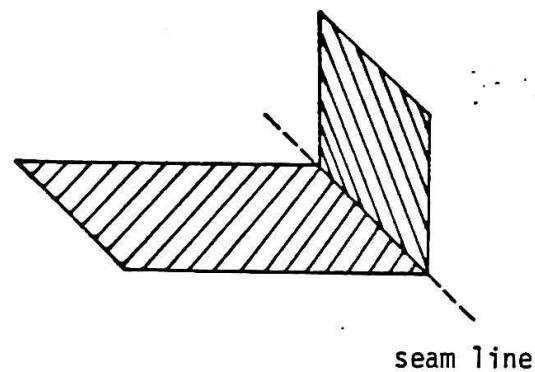
Arc welding, as a line (and, in some cases, volume) process involves additional geometric and kinematic complexities. Motion of the welding torch along the seam must be a smoothly controlled path to maintain a uniform weld seam. Since the arc is affected by the geometric relation of the electrode to the work pieces, motion control must not only move the torch along the proper path, but also control the torch orientation with respect to the work pieces. In order to maintain the proper heating rate of the work pieces, the speed that must be controlled is that of the electrode tip with respect to the work pieces, taking into account any rotation of the torch to track a contour.

Another critical factor is temperature control of the parts at the point of welding. This control is exerted through control of the electrical parameters of the welding operation for spot welding: for specific thicknesses of specific materials, a controlled amount of current is passed through the work pieces at the weld point for a sufficient length of time to melt the work piece surfaces together. For arc welding, an additional parameter that affects heating is speed along the seam. Inadequate control of temperature of the seam boundaries produces bad welds: if the temperature is not raised sufficiently high, the weld penetration will be inadequate, while temperatures that are too high can produce burn through and seam gaps. (See Figure A-2.)

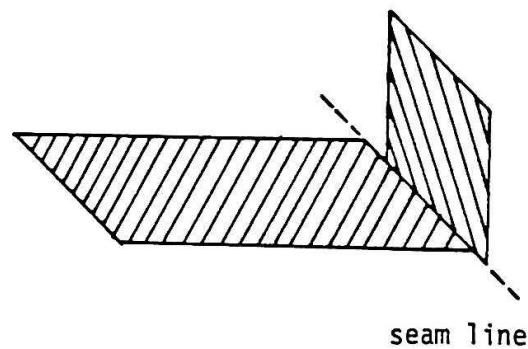
Basic Elements

Mechanical - Robot arms used for welding require a great deal of dexterity in order to properly locate and orient the welding tool, as described in the Process Considerations section. For arc welding, six

(a) ideal alignment



(b) poor set-up,
good seam alignment



(c) good set-up,
poor seam alignment

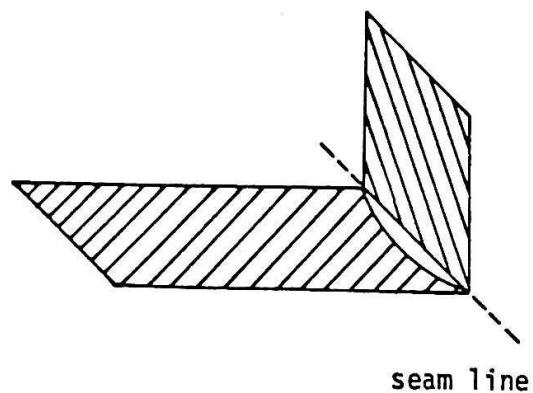


Figure A-1: Parts Alignment for Welding

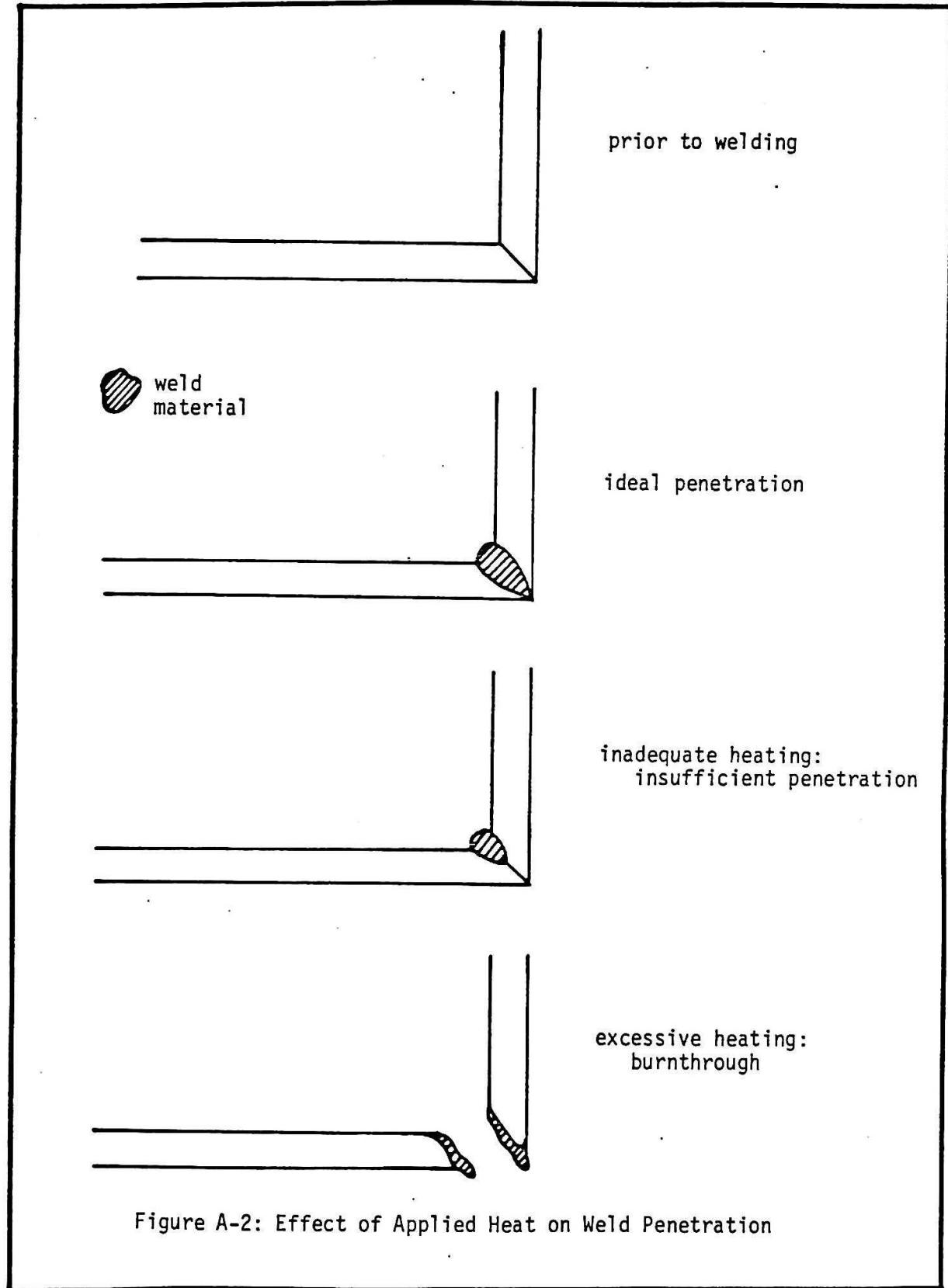


Figure A-2: Effect of Applied Heat on Weld Penetration

degrees of freedom are usually required, three to smoothly control torch location as the seam path is followed, and three to maintain the correct orientation of the electrode with respect to the work pieces. Load capacity is another important aspect of mechanical performance for welding; not only can the welding tools be heavy, but the power leads are thick and rather stiff. Additionally, inert gas arc welding requires a gas supply hose that adds to mechanical load. These supply lines add a component of resistance to flexing at each joint, and require additional force to overcome.

Controller - Spot welding, due to its relative simplicity, can be performed by simple controllers operating in an open loop mode; arc welding requires more sophistication from the controller. Sophisticated path control algorithms are required to move the electrode tip along a smooth path while controlling the orientation and speed of the electrode tip (a much more complicated problem than that of controlling the speed of the end effector). Seam tracking for adaptive path control to accommodate discrepancies between actual and expected seam location requires a controller that can integrate sensory information. Interfacing with the environment for purposes of control of welding parameters (such as arc current or rate of feed of welding wire) can be used to enhance the adaptive capability of a welding robot, but adds to the required sophistication of the controller.

Sensing - The first sensors used for robotic welding were simple tactile probes that rode along the weld seam to guide the welding torch. More recent applications have used through-the-arc sensing, i.e., monitoring welding current and voltage. The principle behind this method is that the position of the welding tip with respect to the surface of the work pieces determines the effective length of the arc which in turn affects the voltage required to maintain a constant current. (See Figure A-3.)

Using an explicitly programmed back and forth motion perpendicular to the seam, a robot can constantly verify the location of the center of the joint, and this information can be used to keep the weld centered on the seam. This same technique has also been used for applications requiring large amounts of filler material to be deposited to reinforce the seam.

Vision sensing is beginning to appear for welding applications in industrial environments, reflecting improvements in flexibility, reliability and cost of robotic vision systems attained in the last several years. Two major problems are being handled with vision systems: seam tracking and weld characteristic monitoring. Visual seam tracking detects the center of the seam by recognizing the discontinuity in reflected light from the two work pieces or by interpreting the image of a strip of light projected onto the seam at an angle. (See Figure A-4.) For weld monitoring, visual systems have been developed that examine the shape and size of the weld puddle. This information can be used to indicate the penetration depth of the weld, whether the weld seam is forming symmetrically and whether the welding speed is appropriate.

Justifications

The consistency of robots in welding is a major advantage over humans.

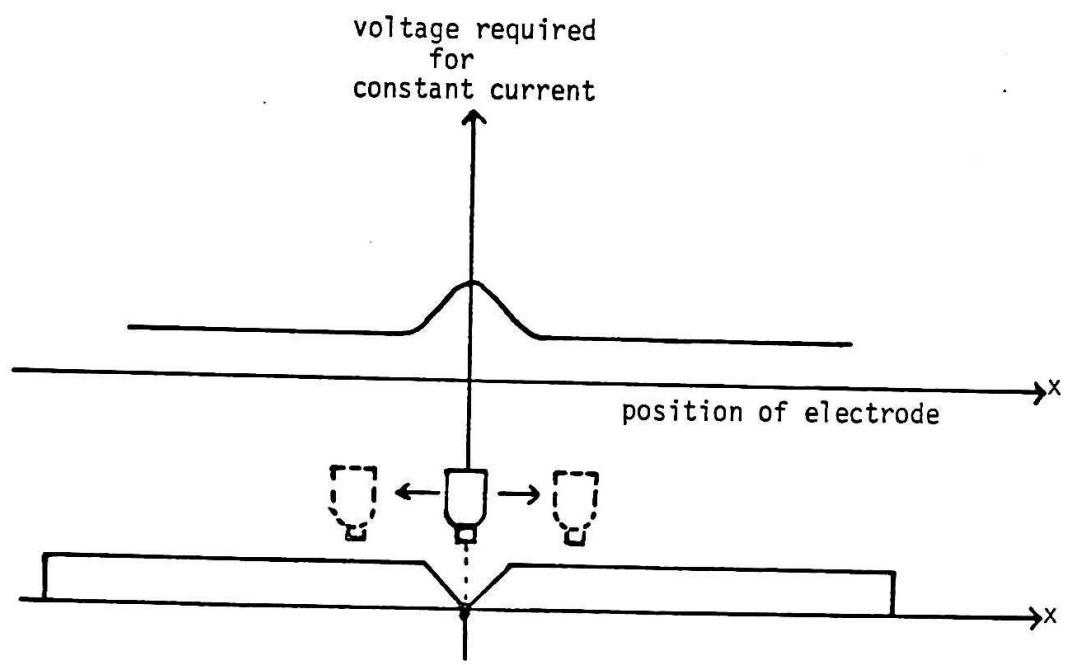
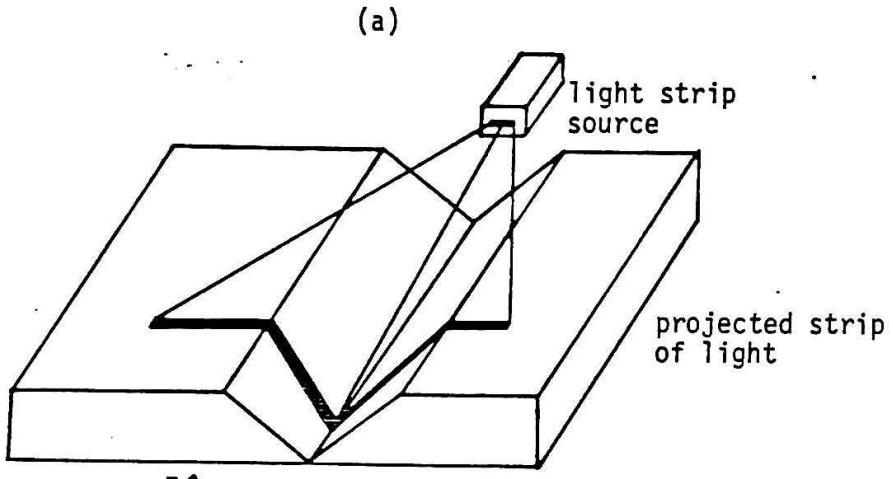
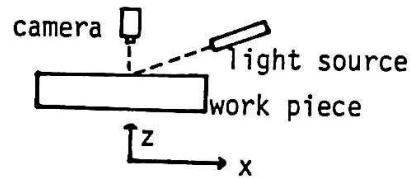


Figure A-3: Through-the-arc Sensing



(b) side view



(c) video image

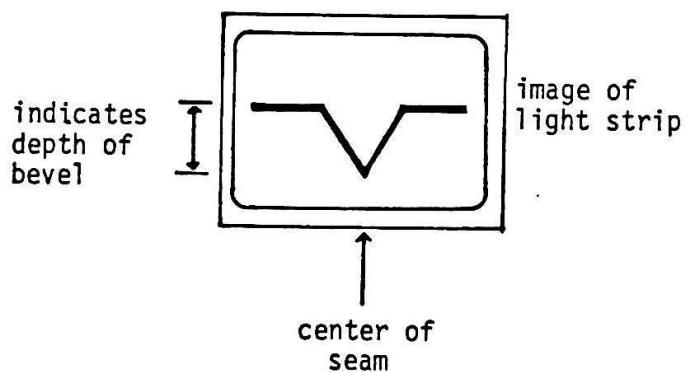


Figure A-4: Structured Light

In spot welding, if an assembly requires twenty spot welds, the robot will always make twenty spot welds (something that apparently cannot be assumed for human welders). If the robot system is properly set up, each weld will be executed properly, even those that are difficult to reach. Consistency with robots is also a major advantage in arc welding: properly set up and supplied, a robotic arc welder will produce a weld, each time, as good as an expert welder will produce at his best.

Environmental factors in welding have an adverse effect on the productivity of human welders. The heat in the vicinity of welding operations can become oppressive, while the fumes, especially when using flux cored welding wire, are unpleasant and can be hazardous. Protective gear, including gloves and especially a welding mask, are heavy and uncomfortable, causing fatigue. Since the arc produces significant amounts of ultraviolet light, exposed areas of skin rapidly develop sunburn, uncomfortable in the short term and potentially hazardous in the long term.

Another major advantage for robots in arc welding is the limited pool of available skilled human welders. Becoming an expert welder requires training and years of experience. This, coupled with the unpleasant aspects of the work, limits the number of people entering the field, while the negative aspects of the work encourage personnel to leave the field. As a result, the supply of expert welders is limited and the cost of using expert welders has risen steadily.

Current Technological Constraints

Current implementations of robotic welding require elaborate and costly fixturing in order to keep deviations in the parts alignment within the relatively narrow range of accommodation and compensation available to today's robots. Improvements in sensing systems are steadily expanding this range of accommodation, but a human expert welder can successfully weld a seam whose mis-alignment is beyond the capability of even a sophisticated robotic welder.

Selection of a sensing system for robotic welders requires serious trade-offs between flexibility and speed. While vision-based systems provide very good adaptive control, they tend to be relatively slow due to the processing requirements of the image interpretation. Visual sensing is further complicated by the light level at the work piece. Two-pass vision systems first scan along the seam to be welded without striking the arc in order to memorize the exact path needed for the weld; this minimizes the vision difficulties but increases the time required for the process and does not allow the vision system to monitor the weld parameters during welding.

There are many applications of welding, especially in shipbuilding, that require very long welded seams, well beyond the reach limitations of current fixed industrial robot mechanisms. Even the work now in progress to develop longer flexible arms will only push this limit back a bit farther. The alternative approach of developing mobile welding robots has run into major difficulties because of the precision needed in locating the welding torch. Inaccuracies in robot location due to shortcomings in the robot's

navigation system and path distortion as a result of drag from trailing power cables have prevented the achievement of sufficiently precise torch location for successful application.

Application Examples

Since the end of 1981, the Locomotive Products Division of General Electric has been using robots to weld bolsters, the structural elements of a locomotive frame on which the power trucks are mounted. Robots are used in conjunction with 6,000 lb capacity positioners to weld these assemblies, consisting of steel plates up to 1 1/4" thick. The introduction of the robots has reduced the time required to perform all of the needed welds to one half of that previously required.

Robots are also used by the Aircraft Engine Business Group of GE to weld stainless steel components of fan frame hubs for jet engines. Cycle time, including part loading and unloading, has been reduced from the four hours required for manual welding to one hour. The actual arc on time with the robot has been reduced to 24 minutes, reducing the heat build-up in the assembly, and the greater precision in control of arc current, torch speed and orientation have improved the quality of final assembly.

2. Material Handling

Material handling, in one form or another, is the basis for virtually all robotic applications. The primary function of a robot is to move an object, be it a tool, inspection device, or work piece, from one point in space to another. In a stricter sense, however, material handling refers simply to moving work pieces. This could include re-orienting, palletizing, or simple pick-and-place operations.

Process Description

Broken down to its basic components, material handling can consist of:

- o locating the object to be moved
- o grasping the object
- o moving the object through a prescribed path
- o orienting the object
- o depositing the object in a prescribed location

Process Considerations

Material handling, though composed of a series of simple tasks, involves some subtle considerations. Locating the work piece, for example, is not a trivial task. Depending on what manufacturing process preceded

the handling step, the work piece may or may not be presented with a known location and orientation. Considerations involved in actually moving the object include the weight, momentum, and inertia of the object and the desired path, acceleration and deceleration speeds. A third process consideration in material handling is the geometry of the object to be manipulated. Small, delicate objects cannot be handled with the same methodology as large, solid objects. How and where objects are grasped can be critically important. A final consideration in material handling is the terminal position of the object. Work pieces which are palletized must be manipulated with much higher precision than those being placed randomly on a conveyor.

Basic Elements

The basic hardware and software elements present in robotic material handling have evolved directly from the process under consideration, for example, the question of locating the object to be moved. Classically, this has been done with the use of elaborate fixturing techniques. If the work piece is always "fed" to the robot in a very precise location, the robot need only to go to that location and grasp the object, unaffected by variations in part location. Fixturing, however, must be specially designed for each application, and is hence expensive. With the advances in sensing techniques such as vision pattern recognition, prices for sensing systems have become competitive with prices for some fixturing systems. Because sensing systems are inherently more flexible than fixturing systems, there has been an increase in the percentage of sensing systems associated with material handling processes, from simple binary verification of part acquisition to complex determination of part location and orientation.

The question of part orientation also has an influence on the elements involved in robotic material handling. Robot manipulator arms are available with different numbers of axes, or degrees of freedom. The more axes a robot has, the more dexterous it is, but also the more expensive it is. For orientation applications, a robot with many degrees of freedom is required. Conversely, simple pick-and-place operations require robot arms with few degrees of freedom.

End effectors have also evolved under the influence of process considerations. Gripper geometries are largely determined by the work piece or pieces involved, and have been generally custom engineered for each application. Current designs include: vacuum, two-finger, and jaw grippers, magnetic pick-ups, and combinations of these.

The robot controllers used in material handling applications have varying degrees of complexity, depending on the other elements involved. The advances in controller capability have been driven by the increasing demands of the specialized robotic hardware developed for individual applications. Robots with six degrees of freedom require a more complex controller than robots with only three degrees of freedom. Current controller technology available for material handling applications include: fine path control, algorithms to calculate kinematic and dynamic properties needed for varying arm speeds and payload weights, obstacle avoidance, complex grasping algorithms, and sensory integration capabilities.

Justifications

The highly repetitive nature of most material handling applications makes material handling an ideal candidate for robotic automation. Any operation as monotonous or tedious as a pick-and-place type of movement, especially with heavy loads, produces worker fatigue. Robot automation removes this from the process. The accuracy of robots is another advantage of robotic automation, especially in a palletizing or de-palletizing operation.

Current Technological Constraints

Even though sensing is becoming more widely used in robotic material handling, there are some advances in sensing technology that would allow robotic automation to penetrate a wider variety of applications. For example, more accurate slip sensing would enable real-time recovery techniques to be more effective; faster pattern recognition algorithms would allow more effective, real-time location, as in the bin picking example.

Application Example

A large Japanese manufacturer has an application example which illustrates several of the beneficial aspects of robotic material handling. In this application, a robot is used to palletize and de-palletize different types of bricks. The robot uses a gripper specially engineered to handle the sometimes brittle bricks with a minimum of breakage. The following benefits were realized with the robotic system:

- 1) Labor savings - With the addition of the robot, one less worker per shift was necessary.
- 2) Increase of productivity - Even with one less worker per shift, productivity doubled.
- 3) Quality improvement - With the specially engineered hand and accuracy of the robot, the defective part rate dropped significantly.
- 4) Safety/Environment - The heavy loads, dust, high temperature and safety hazards of working with the heavy load previously caused a high labor turnover rate. With the implementation of the robot, the manufacturer eliminated its dependence on an unreliable work force.

It should be noted that many of the application examples in subsequent sections are in fact expanded, specialized versions of material handling techniques.

3. Inspection

Process Description

Inspection, as it is performed in the industrial environment, usually consists of examining a work piece either during or just after manufacturing process. This complicates the inspection process, adding

the necessity of determining where and in what orientation the workpiece to be inspected is. For manufacturing applications, a general inspection scheme consists of:

- o getting the part from its previous position
- o establishing a known orientation for the part
- o matching the object with an appropriate reference model or models
- o determining if the work piece is within acceptable tolerances of the reference model
- o sorting the object by part type or quality control

Process Considerations

Selection of the inspection point is the first process consideration encountered in industrial inspection. Ideally, it would be desirable to inspect a work piece through an entire manufacturing process. Economically, however, this is not usually practical. It is necessary, then, to choose the most logically beneficial point or points in the production process to inspect the work piece.

A second consideration in industrial inspection is that of comparison method and thresholding. In general, a work piece can be inspected for many different qualities; it is important for both quality and economic factors to inspect only those properties of a work piece that can distinguish between desirable and undesirable pieces. In addition, it is necessary to determine exactly how close a measured property must be to the reference model to be considered acceptable.

An increasingly important consideration in industrial inspection is that of flexibility. It is often desirable to have the capability of inspecting several different types of parts, either simultaneously or in different batch runs. This requires the ability to accurately choose from among several reference models, depending on which part was to be inspected.

Basic Elements

Robotic inspection is usually performed in one of two modes: either by having the robot move the work piece in front of a fixed sensor, such as a camera, or by having the robot move the sensor around the work piece. In general, it is more efficient to have the robot carry the lighter of the two objects. In either case, it may be necessary for the manipulator to have a high degree of dexterity and accuracy, depending on the geometry of the object to be inspected.

There are currently three main types of sensing hardware available for use: tactile, vision and specially-engineered. Tactile sensors used for inspection can be either point sensing (including simple touch probes or contact switches), or tactile arrays. Although current tactile arrays used in manufacturing consist of binary elements, tactile arrays with force sensing elements have been demonstrated. Vision sensing is also

in one of two modes: imaging, in which an object is noted as either being there or not, with possibly some image enhancement techniques, or pattern recognition, which can include scene interpretation. In addition, there are many specially-engineered sensors such as infrared sensors to detect heat given off by a work piece and magnetically induced eddy-current sensors used in metal-crack detection.

Justification

There are many justifications for using a robot in an industrial inspection scheme. The robot's immunity to fatigue and use of high-precision criteria allows for more consistent quality control and sorting results. Using a robot for inspection may allow in-process inspection to be performed in a hazardous environment. Robots can use sensory properties not available to humans, such as IR and eddy-currents. In addition, the use of robots for inspection allows for the electronic integration of inspection into the manufacturing process, providing an enhanced degree of flexibility.

Current Technological Constraints

The current constraints in robotic inspection concern both software and hardware issues. Pattern recognition algorithms, both for tactile contour maps and visual scene understanding, are too slow to allow real-time processing of the sensory information. Tactile sensing arrays are not sensitive enough to give real-time texture information and the size and cost of most sensing hardware makes it inappropriate or unfeasible in a large number of applications.

Application Examples

A very sophisticated inspection process is used by a major computer manufacturer to orient and inspect keycaps prior to loading them into magazines for use in an automated assembly system. Key caps are shipped in bulk by the supplier, separated by keycap shape, color and legend. Keycaps are dumped into a bowl feeder that orients the caps and feeds them into a track leading to a visual inspection station. This inspection system rejects keycaps with defects, incorrect legends, flawed legends or surface defects, loading acceptable keycaps into magazines that are used subsequently by the keyboard assembly system.

In order for the vision system to "learn" the characteristics of a specific key cap, the operator steps through a menu driven procedure that inputs characteristics of the key (such as light legend on dark background), establishes the inspection window (i.e., what part of the visual field to process) and specifies the legend expected for the key. The system then prompts the user to feed a small number of keycaps known to be good through the inspection system to fine tune the inspection criterion. The result of this learning process is saved on a database and used to provide specifications anytime a batch of that specific keycap needs to be inspected. The entire inspection requires about two seconds per key.

4. Assembly

There are two major categories of assembly applications: closely fitted and easy-mating. The first of these deals with tight tolerance components that are generally fragile and require precise assembly motions. Easy-mating applications generally deal with larger components that are somewhat compliant.

Process Description

- o Acquire parts
- o Orient and Set-Up Parts
- o Perform Assembly - slide, insert, snap, press, stake
- o Inspect
- o Deposit finished assembly (Palletize)

Process Considerations

The range in weight and size of parts to be handled can vary widely, from a small spring up to a cast assembly housing. Furthermore, press fitting or staking as part of the assembly operation may require load capacity (i.e., strength) well beyond the weight of the parts involved. Any tooling that grips the parts must be able to accommodate the variety of shapes and sizes of parts involved in the operation, and handle them gently enough to avoid marring or deformation of sometimes delicate components.

Closely fitted components require precise assembly motions due to their tight tolerances, and may not incorporate any aids in positioning such as beveling or chamfering. Attempting to assemble close tolerance parts that are not properly positioned is likely to damage the parts, ruining the entire assembly. While press fitting is intended to require force for insertion, misalignment of the parts can raise the force required and ruin the parts.

Detection of errors during assembly operations is critical in terms of the unit being worked on and in terms of the assembly process itself. A flawed assembly is not only defective by itself, if it is not detected, it can be incorporated into a larger system that will then also be defective. If a particular step in the assembly sequence begins producing a high error rate it may indicate a problem with the assembly technique or with a batch of components.

Quality control can be implemented as a part of the assembly process and may include inspection of incoming components, inspection during assembly and inspection of the finished assembly.

Basic Elements

Mechanical - Manipulators used in closely fitted assembly are generally

small and precise to match the requirements of a specific assembly task. The required load capacity need not be great, but should be adequate for press fitting, staking or application to assembly of units other than that originally implemented. End effectors used in assembly operations are usually specially designed for the specific parts to be handled. Remote Centers of Compliance (RCC's)* are becoming popular for closely fitted assembly due to their ability to compensate for small amounts of misalignment of parts.

* An ideal RCC is perfectly compliant perpendicular to axis of insertion and completely non-compliant along the axis of insertion.

Controller - Robot controllers for assembly applications can be set up for varying levels of sophistication. If parts are presented in an unstructured way, the controller must have the ability to search for and recognize the parts needed. Low clearance mating operations, since they frequently require positioning accuracy better than the manipulator accuracy, require that the controller be able to use some type of adaptive part mating algorithm for final alignment.

Sensing -

- o **Tactile** - Binary sensing is useful as a simple test of whether or not a part is in place, i.e., to sense that a part has been dropped. Force sensing allows monitoring of parts alignment during insertion since misalignment causes excessive resistance. The abrupt change in applied force when mounting snap-on parts can be used to determine that the part is completely seated.
- o **Vision** - Vision is becoming popular in assembly applications due to its flexibility. It is being used to locate parts for grasping, checking orientation and inspection of parts prior to assembly.
- o **Proximity** - Light Emitting Diodes (LED's) and phototransistor detectors have been placed in the end effectors in some applications as an alternative to binary tactile sensing to verify that a part is in the gripper.
- o **Hearing** - Hearing has been used in assembly operations both to verify that a snap-on part has seated and to detect the sound of a dropped part so that corrective action can be taken.

Justifications

Consistency is a major advantage of robots in assembly work. If the parts supplied to the robot are within specifications and the robot programming is set up properly, the robot will assemble each unit in precisely the same way. In contrast, human performance on monotonous tasks varies, making quality control difficult. Furthermore, human assemblers sometimes apply excessive force to poorly fitted parts in order to finish a unit.

This is a source of marginal or defective assemblies that can be eliminated by programming an assembly robot to limit insertion force.

In a clean room environment, a great deal of personnel time is spent preparing to enter, and the number of times an employee may leave and reenter the clean room per shift can be quite high. Once set up to operate in the clean room, the robot loses no production time leaving and reentering the clean room.

Current Technological Constraints

Parts acquisition is a difficult problem in robotic assembly at this time. Structured parts presentation (e.g., palletized supply, indexed presenter, etc.) solve the problem but can be prohibitively expensive, especially for small batches. Using the robot's sensing capability to locate and orient parts requires sophisticated (by today's standards) and costly sensing and control components. Furthermore, today's technology has not yet completely solved the "bin-picking" problem (acquisition of parts from a jumbled and overlapping pile), although there is a great deal of promising research addressing this problem, and a solution seems to be near.

The fundamental problem of placing one part inside of another part, especially for closely fitted parts, has been taken for granted due to the ease with which a human can solve the problem. However, when applying robots to closely fitted assembly operations, jamming is a common problem and many current algorithms to improve parts alignment reduce the speed of the operation noticeably. While currently available RCC's are helpful, their range of accommodation is not large, they are not programmable, and they are not totally successful in preventing jamming due to misalignment. Current work on the generic "peg-in-a-hole" problem and the explicit geometry of jamming are likely to result in more effective and more efficient methods of assembling tight tolerance parts.

At this time, error handling methodologies for assembly sequences still require improvement. Not only should an error during assembly be detected, but recovery from the error should be attempted. Whether recovery consists of discarding the entire assembly and starting over or discarding a single part and trying again should be determined by the type of error and the part of the assembly sequence involved. At this time, most assembly robots, when an error is detected, simply stop and wait for human assistance.

Application Example

An interesting example of robotic assembly has been shown by SRI, using two coordinated robot arms, one with a force sensing wrist and the other with a hand mounted camera to assemble a part of a printer carriage. There are four types of parts involved in this assembly, a square shaft with four plastic rocker arms already attached, four plastic rockers that snap into the rocker arms and two sizes of roller shafts that snap into the rockers. The sequence begins with Arm number 1, the one with the camera attached, picking up the shaft/rocker arm assembly and placing

it in a specially designed support fixture. Arm 1 then acquires rockers and places them in the correct location with respect to the rocker arms. Arm number 2 is used for assembly because of its force sensing capability. The force exerted by Arm 2 is monitored as it presses on the rocker, with seating indicated by a rise in force followed by an abrupt drop as the rocker snaps into place. While this is being done for all four rockers, Arm 1 has placed the roller shafts in an aligning fixture. In the next step, Arm 1 lifts the shaft/rocker arm/rocker assembly and turns it over, placing it on top of the fixtured roller shafts. Arm 2 then pushes down on each rocker until it snaps onto the roller shafts. Force sensing is again used to sense completion of the snap fit.

5. Painting/Coating

There are a variety of ways to apply coating materials to objects that will be included in this application. Painting can be performed by techniques ranging from dipping to electrostatic spraying. While not dealing with paint, thermally sprayed coating to produce a metallic surface is included because the method of deposition is very similar to spray painting. Of these methods, spray painting is the most common in manufacturing, and is the primary focus of this section.

Process Descriptions

Dip Coating:

- o lower work piece into coating material reservoir
- o lift out
- o allow to drain; spinning can be used to remove excess

Flow Coating:

- o pour paint over work piece
- o allow to drain

Paint Spraying:

- o atomize paint
 - air spraying uses the violent mixing of paint with high pressure air
 - airless spraying applies pressure directly to force paint thru nozzle
- o direct paint to target
 - air and airless spraying use residual momentum from the atomizing process
 - electrostatic spraying uses electrical attraction between the charged paint droplets and the oppositely charged target.

Thermal Sprayed Coating:

- o melt coating material
 - Flame spraying feeds coating into gas (e.g. propane) flame
 - Arc spraying feeds coating material through

- an electrical arc
- o atomize molten coating material with compressed air jet
- o direct spray to target

Process Considerations

The goal of painting/coating applications is generally to achieve an even, controlled thickness, coating on the target. Too thick of a coating is wasteful and may cause problems due to excessive drying time while too thin of a coating may defeat the purpose of the process. In dip and pour coating, control of the viscosity of the coating material and manipulation of the object during the draining (e.g., tilting, spinning) are used to control the coating process. In spraying operations, coating thickness and evenness are determined largely by the path and speed of the spray gun with respect to the target. A successful coating requires that the spray gun be moved smoothly along its path, maintaining a constant distance and speed while following the contour of surface to be painted. This path control problem becomes more complex when the object to be painted is moving along an assembly line or requires manipulation, such as door opening in automotive applications, during the painting process.

The painting of large assemblies requires mobility from the painter, and increases the difficulty of producing an even coating due to the distance over which the evenness must be maintained. Convolved and partially enclosed structures are especially difficult to paint, requiring that the spray gun be moved into confined spaces and carefully manipulated to provide even coverage of interior surfaces.

The environment in which spray painting is performed is a harsh environment since the process itself generates solvent vapors and a paint mist that envelop the work area. Personnel working in the vicinity of painting operations wear protective clothing and breathing gear to reduce exposure to these hazards, but the price of protection is worker discomfort and fatigue. Not only is this environment unhealthy, but the risk of fire or explosion is severe. The accumulation of paint mist in confined spaces can become severe enough to reduce visibility, and paint buildup on surfaces and equipment requires frequent removal.

Basic Elements

Mechanical - Dexterity is needed by the robot manipulator arm; five degrees of freedom allows painting of three dimensional surfaces although one or more additional degrees of freedom or mobility enhance the ability of the robot to reach interior spaces. Actuators must be explosion proof due to the flammable atmosphere; as a result, hydraulic actuators are generally used.

Large assemblies require robot manipulators with large work volumes or some form of mobility such as a rail transport system. End effectors usually consist of permanently mounted spray guns, although some models allow a walk-through teaching handle to be attached.

Controller - The primary task of robotic controllers in spray painting applications is to provide smooth continuous path control along the surface being painted. Virtually all of the current robotic painters are programmed by the walk-through method in which a skilled painter physically moves the robot arm along the desired path while the robot records the required motions. The moving target situation can be programmed in this way with the constant speed of the target added to the learned path by the controller. Editing capability is highly desirable to allow corrections or adjustments of the program, since changes to walk-through taught programs generally require that the entire program be retaught from the beginning.

Sensing - Very little sensing is incorporated in painting robots; satisfactory results are achieved with good path control, carefully taught programming and reliable painting equipment.

Justifications

The improvement in consistency is an advantage of robots for all of the painting/coating applications. Once successfully programmed, a robot will turn out properly painted or coated pieces time after time, unaffected by fatigue, paint fumes or boredom. Not only does this consistency raise the quality of the process, it also reduces the waste of deposited material due to the precision of its path and spray stop and starts. Overspray can be minimized when programming, and the robot will repeat this savings every duty cycle.

Removing personnel from the spray painting environment not only protects their comfort and health but also reduces the ventilation requirements for the spraying area which are based on hazard to humans. The energy required to heat or air condition the fresh air brought in for the painter is substantial, and increasingly stringent standards on venting of contaminated air require more and more sophisticated and expensive cleaning of paint laden air before it can be released.

As in arc welding, the skill required of a human painter to produce high quality paint finishes quickly is the result of training and experience. Reducing the standards required for a painter expands the pool of available personnel, but may require slowing down the assembly line, increasing the number of units requiring correction or allowing quality control standards to slip. Robots offer a solution to the problem of conflicting demands for higher productivity and quality versus human aversion to working in unpleasant and unhealthy environments.

Current Technological Constraints

Current industrial painting robots incorporate little or no sensing. As a result, there is virtually no fault detection capability incorporated in the robot. Inspection of surfaces prior to coating for dents, gouges or contamination, if performed at all, is done by human inspection. Process monitoring is largely restricted to detection of gross failure of the painting equipment, such as a clogged paint nozzle. Current technology could be applied to provide constant monitoring of the spraying process, including average droplet size and velocity and paint spray density.

This type of monitoring would allow adaptive reaction to fluctuations in the paint supply, improving quality control and reducing the incidence of parts requiring repainting.

The walk-through programming method most commonly used for painting robots is cumbersome. While current users, whose painting is predominantly large batch, consider this time consuming set up process acceptable, users who operate on smaller batches would find it uneconomical. Additionally, the very high cost of painting robots is a major barrier to the use of robots for small batches.

Application Examples

A manufacturer of molded plastic parts for the audio industry has installed a robot to do the final painting. The robot uses a 5 DOF articulated arm with 32K words of available memory, programmable with either continuous path or point to point motions. Parts handling is accomplished by means of a double conveyor system arranged in a "V" pattern on either side of the robot. This arrangement increases the through-put of the system. In addition to the advantages of removing workers from a dangerous environment and reducing the company's dependence on skilled labor, the manufacturer has seen a 140 percent increase in daily productivity as well as an eightfold reduction in defective parts.

General Motors has recently installed what they believe to be the most advanced painting system in use at their Doraville, Georgia, assembly plant. The painting system consists of one painting robot and one door-opening robot mounted on tracks on each side of an assembly line. All four machines operate under computer control. The path tracking is accomplished by operating a single robot in the teach mode and then mirror-imaging the taught path into the robot on the opposite side of the line. With this system GM claims to be able to paint all external surfaces plus interior surfaces such as station wagon tailgates, deck lids, pick-up truck beds, door hinges, and door openings.

6. Other Applications

6.1 Sealing/Bonding

Process Description

Although each bonding application will have its own specific considerations, there are several generic steps that must be performed in a bonding application. These include:

- o securing the work piece to a fixed, known position
- o applying the bonding material
- o aligning the work pieces
- o fixing the work pieces together

Sealing applications may involve two work pieces, or may involve simply covering a hole in one work piece.

Process Considerations

In sealing and bonding, one of the major application considerations is the speed at which the material sets up. Because of the short working time of most commercial bonding materials, successful applications require a well controlled and coordinated process scheme. The applicator speed must be adjusted to give a minimum application time, as well as be coordinated with the material pumping and flow rates to ensure that a consistent bead of material is maintained. The path must be well planned to cover an appropriate area with economy of both time and material. In addition, the applicator must be accurately controlled through this path, in each repetition to maintain economy.

Basic Elements

The basic robot requirements for sealing and bonding are similar to those necessary for paint spraying and arc welding. These include five or six degrees of freedom in the manipulator for dexterity and continuous path control capabilities in the controller. End effectors for sealing consist of specialized sealant applicators mounted directly on the end of the robot arm. Controllers for bonding robots usually have the ability to directly control the flow rate of the sealant through the nozzle. Vision systems and specialized air jet sensors have recently been used to detect breaks in the material bead, and the weight of the material container is monitored to prevent the supply pump from running dry.

Justifications

The high repeatability of a robot can significantly reduce wastage in this application since the robot, once programmed with an economical path, will follow this path more closely than a human worker. Robots can increase productivity by applying sealing or bonding material faster than a human, and by eliminating the fatigue that results from manipulating the heavy adhesive gun. A final incentive for the use of robots is the removal of human workers from an environment of very high temperatures and noxious fumes.

Current Technological Constraints

Because sealing applications are fairly straightforward, most problems encountered can be solved with proper planning techniques. One problem that has not been solved yet, however, is that of error handling. Although sensors can detect a missed section of bead, appropriate methods are not yet available for returning to repair the gap.

Application Examples

At a General Electric Company in Kentucky, a robot is being used to apply a foamed hot melt adhesive to seal perforations in refrigerator cases. Refrigerator cases are transported horizontally along a conveyor to the sealing station, where they are automatically tipped so that the holes to be covered are on an angle. The robot applies a metered amount of sealant above the hole and gravity pulls the sealant over the hole to seal the hole.

6.2 Finishing

Because the manufacturing definition of finishing processes differs from the general use definition, we give here a brief explanation of finishing as it applies to this report. In general use, finishing usually refers to painting or coating type operations, performed as the last step in the manufacturing process. In the strict manufacturing sense, however, finishing refers to a category of cleaning processes, such as trimming flash from castings, sanding, deburring, and polishing. For the purposes of this report, finishing will refer to the strict manufacturing definition.

Process Description

Finishing usually consists of one or more of the following operations:

- trimming flash, by:
 - o saw trimming
 - o spark cutting
 - o laser cutting *
- grinding flash
- sanding
- deburring
- polishing *

Process Considerations

The first consideration in the finishing process is the shape of the part to be processed. The part, usually a casting, will be "raw" in the sense of having unpredictable burrs and pieces of flashing in unknown positions. The scattered flashing and heavy weight of the work piece make manual handling potentially dangerous and automated handling difficult. Depending on the condition of the work piece, it may be necessary to perform a combination of finishing operations, with or without inspection between the process steps. The cleaning processes themselves must be considered both to prevent deformation of the work piece, and to minimize the production of irritants such as dust and grit.

Basic Elements

There are two generic modes in which finishing operations are performed.

In one mode, the finishing tool, such as a grinding wheel, is fixed in a permanent position. The robot picks up the work piece, orients it, and passes it over the tool in a prescribed path. In the second mode, the work piece is positioned in a jig, and the robot moves the finishing tool. Payload weight can determine the mode selected: it is usually desirable to have the robot hold the lighter of the two objects. If the robot holds the tool, it may either hold the finishing tool in a standard gripper, or have the tool mounted permanently on the robot arm.

Specialized controllers and sensors are important for finishing operations. The relative needs for each of these are interdependent. If there is no sensing involved, the robot needs a very accurate model of the finished part, stored in a database, to which it can refer during the finishing operation. On the other hand, an integrated system using vision to detect flaws and force sensing to guide the finishing tool, would not need such a detailed model. Current state of practice is to use a simple internal model of the part combined with low-level sensing, such as force sensing.

Justifications

Human workers in the finishing environment are exposed to a variety of hazards, including high noise levels, airborne dust and grit, and disintegrating grinding wheels. Robots can remove humans from these dangers, enhancing plant safety.

Current Technological Constraints

Although force sensing provides an adequate means of controlling an operation such as grinding, the robot must still be programmed to traverse the entire workpiece. Additional sensing such as vision could be used to guide the finishing tool to only those areas of the work piece that require cleaning.

Application Examples

A Swedish foundry has installed a two-robot system for grinding operations. The first robot carries a permanently mounted grinding wheel and is used to cut ingots. The robot is equipped with both force and torque sensing, the latter used to detect wheel wear. Work pieces are fixtured on a rotating, two-position work table. The second robot handles the ingots directly, passing them by several finishing machines composing a work cell.

A truck manufacturer is using a robotic system that finishes cast iron gear housings. In the first step of the process, the robot arm picks up an abrasive cut-off wheel driven by a hydraulic motor that is used to remove risers and external flash from the raw casting. In the second stage, the robot replaces the cut-off tool with a gripper that picks up the casting and moves it to a floor mounted grinder. Before grinding, a sensor on the robot arm locates the surface of the grinding wheel to set a reference that compensates for wear of the wheel. The

casting is then moved against the wheel to remove the parting line along the outside diameter of the casting. Flash is removed from the inside of the casting by positioning the casting over a floor mounted impact tool fitted with a chisel. The final finishing step, deburring inside surfaces, is performed by moving the casting to a floor-mounted abrasive deburring machine. This deburring machine includes automatic wear compensation and programming to shut down the system in the event of tool failure. The robot operates unattended during the night shift, with tool replacement and maintenance being performed during the day shift.

6.3 Investment Casting

Process Description

Investment casting is based on single-use molds; a new mold must be formed for each casting. The molds are formed in the following way. First, a wax model of the part is formed. The model is then coated with a lubricating and releasing agent. The mold is then dipped into a ceramic slurry, and coated with sand. The slurry/sand mixture is allowed to dry, and the dipping is then repeated. After five or six coats, the mold is placed in a heating unit, usually a steam autoclave, to melt out the wax model. The hollow mold is then fired in a kiln and used for the metal casting.

Process Considerations

The most critical consideration for a successful investment casting is quality control of the ceramic shell. Consistent thickness of the individual coats of ceramic slurry will result in a more uniform and higher quality finished shell. The dipping, rotating, and swirling motions while the mold is in the slurry are all important factors in the final coat thickness, and must be carefully controlled. Other considerations in investment casting are the wide range of weights to be lifted from the beginning to the end of the coating cycles, and the time and temperature control necessary during the drying cycle.

Basic Elements

The basic robot elements necessary for investment casting operations are similar to those required for dip painting. In addition, it may be necessary to have a particularly robust manipulator to handle the weights involved; in some applications payloads can weigh hundreds of pounds by the end of the dipping process. A desirable, though not essential, robot element used in investment casting is a flexible, easily re-programmable controller. Easy re-programming allows for economical small batch jobs.

Justifications

A robot is well suited to performing the dipping operations for investment casting because the key to a quality shell is the consistency of the slurry

coats. Once a successful pattern of dipping, rotating and swirling the mold in the slurry is programmed into the controller, the robot will repeat those motions exactly. Another factor favoring a robot to perform the dipping operations is fatigue. The heavy weights involved often cause fatigue in human workers who dip the mold, reducing consistency and productivity.

Current Technological Constraints

The high cost of current robotic systems is not always justified for those applications where very small batches are common.

Application Example

A manufacturer of marine outboard engines has been using robots in their investment casting applications since 1974. The implementation is straightforward and required a minimum of plant reorganization. At full manufacturing output, this company produces many different types of castings, ranging in weight from 1/4 to 8 1/2 lbs. Each type of casting requires six individual coating cycles, with specific dipping and swirling motions. The robot controller is responsible for cycling the slurry bath motors as well as the fluidizing bed air supply. This robot implementation has increased both output and casting quality.

6.4 Die Casting

Process Description

The die casting process, unlike the investment casting process, re-uses the mold in which the product is cast. This necessitates additional steps to maintain the quality of the mold. The process as a whole consists of:

- Preparing the die
 - o clearing the mold of any obstructions
 - o lubricating the mold
- Pouring the liquid
 - o checking the temperature of the liquid metal
 - o controlling the pour rate of the liquid
- Controlling the time and temperature of the cooling cycle
- Extracting the workpiece from the die
- Checking the mold for parts remaining in the die

Process Considerations

There are several variables which must be carefully controlled for a successful die casting. These include temperature, which must be controlled for molds to be predictable, and cooling time. There is a delicate balance between the metallurgical requirement for adequate cooling time and the economic need for short cycle times. Die cleaning and lubrication between cycles must be thorough and consistent to prolong die life and give higher quality castings. A final consideration in die casting is safety when handling molten metal.

Basic Elements

The basic robot requirements for die casting are similar to those involved in general material handling, i.e. average manipulator dexterity. In addition, there are several robot elements that are especially useful in the die casting environment. These include temperature protected end effectors, which are necessary when working at the high temperatures involved in die casting, and smooth path control. Although not necessary for simple work piece handling, smooth path control becomes useful in the delicate mold cleaning process.

Justifications

An important reason for choosing a robot to work in a die casting environment is the consistency of the robot. The high repeatability of the robot can reduce scrap by as much as 20%, thus increasing productivity and decreasing re-melt costs. Furthermore, consistent and accurate die cleaning can significantly increase the useful lifetime of the die. Removing humans from a hazardous environment and having the capability of integrating the casting and finishing operations are additional reasons to use robots.

Current Technological Constraints

Although robotic die casting is fairly straightforward, there are several sensing capabilities that would enhance the current state of practice. These include better detection of incomplete part removal from the die and better real-time temperature sensing and control during the cooling process.

Application Example

Du-Wel's casting plant in Dowagiac, MI., casts parts for a variety of users, including automotive and appliance manufacturers. One of their most successful robot applications consists of servicing two die casting machines. The robot loads one machine, turns 180°, unloads the other machine, sprays the die with lubricant, deposits the piece into a quench tank, reloads the machine, then turns back to the first machine.

6.5 Forging

Forging, although an important backbone of many manufacturing processes, is in fact a very simple operation.

Process Description

At its greatest level of complexity, forging consists of:

- o acquiring the work piece
- o placing the work piece in a furnace
- o transferring the heated part from the furnace to a forging press
- o cycling the press
- o removing and quenching the work piece
- o inspecting the work piece
- o depositing the work piece

Process Considerations

Although a simple process, forging does require careful control of several variables, namely timing and temperature. The pre-forging temperature of the work piece must be precisely controlled for consistently successful forging. This can be accomplished by altering the time that the work piece spends in the furnace, by altering the furnace temperature directly, or by a combination of both. After forging, the work piece may need to be quenched. Improper quenching times or temperatures could result in undesirable crystallization of the metal. The environment of dirt, smoke, noise and high temperatures typical in a foundry is an additional consideration that affects productivity.

Basic Elements

The basic robot elements necessary for forging applications are similar to those required for general material handling, i.e. average dexterity in the manipulator movements to acquire, orient, present and remove the workpiece from the furnace and press. Variations of robot elements that are used in forging applications include specialized end effectors, sensors and controllers. The end effectors used in forging must be heat-resistant. The high temperatures involved in forging can easily damage the hydraulic or electric systems of an unprotected end effector. Sensors that are used in forging have been developed to take advantage of the forging conditions. For example, infrared sensors are used to detect the position and status of a work piece based on its heat output. Robot controllers used in forging applications are usually modified so that they can communicate with their environment, e.g., the controller is equipped to sense and/or control the furnace temperature, or to cycle the presses.

Justifications

The harsh environment of the work place is probably the most important justification for using a robot in forging applications. Because of the heat, dirt, noise and smoke, a human may need to take as much as three to four hours of breaks during one production shift. A robot can usually run continuously, unhampered by the environment. In addition, the precise nature of the robot controller allows very accurate and repeatable timing and motion control. This increases the consistency and quality of the forged parts.

Current Technological Constraints

While current robot controllers are capable of real-time temperature sensing, they are not sufficiently sophisticated for adaptive control of timing and temperature.

Application Example

An aircraft engine manufacturer has successfully incorporated a robot into the upset forging process in the manufacture of jet engine airfoil blades. This application begins with the robot acquiring the raw part from a vibrating parts feeder/orienter. An infrared sensor is used to check that the feeder is in fact loaded. The robot loads the part into a standard rotating hearth furnace, coupled to the robot controller. The temperature of the furnace is sensed by thermocouple sensors which detect simple over or under threshold conditions, while the position of the table is controlled by a stepper motor. After the hot workpiece is removed, the robot controller causes the furnace door to close, checks to see if the part is in fact in the gripper (by means of another IR sensor), instructs the manipulator to load the part into the press, then cycles the press. After cycling the press, the controller signals the press to eject the part, checks to verify that there is no part in the press, and then repeats the entire process.

6.6 Plastic Molding

Process Description

As with die casting, the individual processes associated with plastic molding are simple. The plastic molding cycle consists of:

- o loading the plastic charge into the die mold
- o loading the die mold in the molding machine
- o cycling the molding machine
- o extracting the molded part
- o inspecting and finishing if necessary

Process Considerations

Plastic molding is similar to die casting in that it involves most of the same process considerations as die casting. Among the more important are: time and temperature control, consistent and accurate die cleaning and lubrication, balancing the need for adequate cooling time against the need for fast cycle times, and the harsh environment of the molding workstation. Specific to plastic molding, however, are the noxious fumes given off by the molten plastic, and the delicate handling requirements of the pliant plastic.

Basic Elements

The basic robot requirements for plastic molding applications are similar to those of general material handling. Useful robot element variations for plastic molding include specialized end effectors and controllers. To speed cycle times, the robot must handle the molded parts while they are still warm. The end effectors used for this handling must be able to manipulate the hot, compliant parts without deforming them. As in die casting, the robot controller must be interfaced with the peripherals that it will be controlling, such as the molding machine.

Justifications

The justifications for using robots in plastic molding are similar to those in die casting. These include increased quality due to the control, consistency and repeatability of the robot, and the removal of workers from the hazardous environment.

Current Technological Constraints

The major technological barriers to the increased use of robots in plastic molding involve sensing and control. Current sensing systems cannot detect small parts of the molded piece adhering to the die rapidly enough to avoid interfering with the cycle time. As a result, robotic systems either leave occasional remnants in the die, which ruins the next molded part, or clean the entire die each cycle, which reduces the lifetime of the die.

Application Example

An appliance manufacturer is using robots in the molding of vacuum cleaner parts. A pick-and-place robot removes two molded parts at a time from a dual cavity injection molder, using a specially designed twin gripper. The robot presents each part to a broach machine for sprue removal and then deposits the parts on a cooling conveyor. The elimination of an unpleasant and hazardous job was the primary motivation for installing the robot, but the increased productivity due to the robot allowed an investment payback of less than two years.

Appendix B

Industrial R&D Activities

In this appendix, we will briefly describe R&D programs of individual companies active in the field of robotics, including both producers and end-users. This list is of course limited by the availability of information concerning private companies.

Producers:

Westinghouse/Unimation

With the acquisition of Unimation, Westinghouse became one of the larger companies to manufacture robots both for sale and for in-house use. The majority of the research performed, however, remains largely centered on application development. One of the on-going projects concerns the development of an automated turbine blade inspection system in their Winston-Salem plant. Westinghouse is working closely with Carnegie Mellon University on the development of this software-intensive project. Several other projects include the automation of circuit board assembly in several different plants, and the development of a laser manipulator tube for the Nirop plant in Minneapolis. Past projects have included development of the APAS assembly system and several vision inspection systems.

Prab Robots

Prab robots has as one of its corporate philosophies the view that the simplest robot that can perform the job should be used for the job. For this reason, Prab tends to spend a good portion of its relatively small R&D budget not on new, leading edge technology but on adapting their robot lines for use in various established industries and applications, such as palletizing, parts transfer, and machine tool load/unload.

GCA

GCA's corporate strategy is inclined towards development of complete automated manufacturing systems. GCA has acquired several smaller companies and licensed appropriate technologies in an effort to create an immediate market presence in the field of flexible manufacturing, while at the same time integrating these technologies through the strong software design capability of their Industrial Systems Group. One of the most important projects involves the development of an advanced controller capable of complete integrated system control.

GE

At the Corporate Research Center in Schenectady, research projects

range from basic to developmental. On the basic research end, projects on vision, tactile sensing, and process planning are in progress. Application research centers on assembly, laser machining, and arc welding. The arc welding project has produced "Weldvision", a novel method of monitoring the weld puddle to control the arc welding process. Smaller projects scattered around the corporation include off-line programming development and local area networking.

GMF Robotics

While the majority of the basic research efforts of GMF are performed by Fanuc in Japan, GMF performs some application development work in the U.S. Highest on the list of priorities is research in vision systems. Other projects include work on quick-change robot components for a modular robot and development of application-oriented off-line programming.

IBM

While IBM originally concentrated their robotics efforts on application-oriented developmental work, recently they have shifted their emphasis to more fundamental issues necessary for the development of their own robot lines. Current work centers on simple 3-D and sophisticated 2-D vision, geometric modelling, various assembly issues including compliance, and intelligent software support. In the past, research efforts have included development of the process oriented programming language AML, as well as the assembly gantry robot, model 7565.

Automatix

Research and development at Automatix is focused in two directions, vision and control. Vision research, on which Automatix built its reputation, currently centers on developing an inexpensive, fast 2-D vision system as well as development of 3-D vision. The vision research has led Automatix into the control area, which currently includes sensory-based control for seam welding and control for a flexible manufacturing system.

Adept Technology

Much of the current work on process-oriented language and system design at Adept Technology is an extension of the software effort, specifically VAL-II, that was developed by Adept Technology when it was known as Unimation West. While this work is still important, other projects at Adept include development of a three-wheeled mobile cart on which a PUMA robot can be mounted, a six degree of freedom manipulator, a high speed servo control system, a new robot using direct drive actuators and several vision sensors.

Allen Bradley

Allen Bradley is a component manufacturer specializing in controllers.

In addition to research efforts aimed at increasing the sophistication of their existing controller lines, Allen Bradley currently is involved in the development of an advanced programming language based on the Pascal language. More developmental work is currently underway in the area of AC servo drives.

Lord Corporation

The Lord Corporation is a component manufacturer, specializing in tactile sensors and tactile sensor control algorithms. Researchers at the Lord Corporation are working very closely with the tactile sensing laboratory at Case Western Reserve University. In addition to tactile sensing research, Lord Corporation has begun work on 2-D vision for inspection.

Fared

The Fared group of companies is composed of three robot producing firms. Fared Robot Systems has as its R&D thrust the development of an assembly robot to handle clean room applications. Robot Defense Systems is concentrating on an autonomous mobile robot for security. Farad Drilling Technologies has developed massive robots capable of lifting 5,000 lb. pipe sections and currently conducts R&D on controls for these robots.

Cincinnati Milacron

Cincinnati Milacron is one of the pioneer robot producers. They include vision sensing, control system architectures, programming languages and integrated manufacturing systems among their R&D programs. Specifically, current projects are concentrated on combining laser technology with robotics, and automating the production of structural components out of advanced composite materials.

Machine Intelligence Corporation

Machine Intelligence Corp. is developing work cells which incorporate robots, micromanipulators, lighting systems and machine vision systems for use in the semi-conductor and computer-peripheral industry. These fully integrated systems are designed to perform precision measurements in the micro-realm for in-process inspection and statistical quality control for fully automated production lines.

End-Users:

McDonnell Douglas

Robotic R&D efforts at McDonnell Douglas are concentrated on off-line programming and system control. McDonnell Douglas is assessing the capabilities of the programming language MCL for off-line programming, and the

use of MCL in an actual production mode. In another effort, the language system RAPT (developed by researchers at Edinburgh University in Scotland) is being used for intelligent reasoning on a database of geometric models. In the past McDonnell Douglas has developed several modeling and simulation software packages, including one known as "Place".

Northrop

In addition to several classified robotics projects, Northrop is developing robotic capabilities for aircraft parts manufacture and inspection. Specifically, Northrop is studying automatic placement of carbon-impregnated fabric in the manufacturing process of airplane wings, automatic drilling of holes in wings, and visual inspection of material texture. For the visual inspection project, Northrop is studying the applicability of 3-D vision.

Hughes

Research at the Hughes Research Laboratories is concentrated on the development of an intelligent, autonomous system. Research issues include: knowledge-based systems, image analysis, navigation, goal monitoring and planning.

Fairchild

Fairchild robotics research is unique among end-user R&D in that it is concentrated almost exclusively on fundamental, basic research. Issues under consideration include: 3-D vision, specifically for use in IC inspection, intelligent systems for VLSI design using PROLOG, and knowledge representation.

General Dynamics

General Dynamics is relatively active in aerospace robotics R&D. Beginning in the 1970's with the Air Force ICAM project, General Dynamics has led a strong program in application specific development, most notably the wing drilling project. Currently, R&D work at General Dynamics is focused on system integration.

GMC

The largest robot user in the automotive industry, GM has several research and development projects in progress. The largest of these efforts is the development of their NC painter, a painting system project whose goal is to remove human workers from all aspects of the painting process. Other projects involve vision research based on a CAD modeling system, and some assembly work directed at complex engine subassemblies.

Appendix C

Not-For Profit and Academic R&D Activities

This appendix is included to give the reader a more in-depth view of the size, scope and directions of NFP and academic R&D programs than was practical to list in the text.

NFP:

Although there are at least four non-profit research centers participating in robotics research, the two which sponsor the largest programs are the Stanford Research International Laboratory (SRI) and the Charles Stark Draper Laboratory.

SRI has been conducting research in robotics since the SHAKEY Artificial Intelligence Project, begun in the late 1960's. Current research at SRI covers a broad range of areas, with an emphasis on vision. SRI developed the first algorithms for binary image processing and continues to develop binary and gray scale vision for depth perception and parts recognition. Other projects include vision controlled arc welding, assembly, semi-automatic process planning, circuit board inspection, voice control and flexible grippers.

The Charles Stark Draper Laboratory has conducted research in a number of areas, such as real time simulation of the space shuttle's robot arm, 6-axis force/torque sensors and batch assembly processes. Research has also included accommodators for robot wrists which allow tight fitting parts with varying tolerances to be assembled without additional movement of the robot arm.

There are two other non-profit research centers active in robotics research, the Jet Propulsion Laboratory (JPL) of the California Institute of Technology and the Manufacturing Productivity Center of the Illinois Institute of Technology Research Institute. The robotics effort at JPL consists of 14 staff members and includes research in sensor-based control, teleoperators, multiple finger grippers and artificial intelligence. Efforts at the Manufacturing Productivity Center include research in sensors, controls, assembly, welding and material handling.

Academic:

Carnegie Mellon

At Carnegie Mellon University (CMU) there are presently 72 researchers devoted wholly or in part to robotics research. This makes CMU the largest robotics research center in the country. Funding for CMU comes from both government and industrial sources. In FY 82 CMU received a total of approximately \$4 million for research. Over two million of this was from industrial sponsors, such as Westinghouse and Digital Equipment. The Office of Naval

Research (ONR) contributed about half a million dollars and the National Science Foundation (NSF) \$375 thousand in FY83.

The key areas of research at CMU are sensing, programming, arm and gripper design, mobility and factory automation. One example of their sensory research is a proximity sensor which utilizes six infrared LEDs in a circular pattern and an analog spot position detector chip. The sensor is used to determine surface characteristics and position to an accuracy of 0.1mm. CMU is also developing a direct drive manipulator, the DD Arm, which is driven by rare-earth magnet DC torque motors. These motors, due to their low operating speeds and low weights, are used not only as actuators but also as joints. This design eliminates transmission mechanisms, thus increasing efficiency and eliminating backlash problems.

Stanford University

Research efforts at Stanford have been, primarily, in force sensing, vision and programming languages. Their most significant advances have been in programming. Stanford has developed one of the most advanced programming languages, the Arm Language, or AL, as well as ACRONYM, which is used for robot programming, geometric modeling and reasoning in model based vision systems. Workers at Stanford have also developed a software package called SIMULATOR for use in off-line programming, which allows users to test programs prior to use.

Massachusetts Institute of Technology

Robotics Research at MIT is conducted in the Artificial Intelligence Laboratory and the Mechanical Engineering Department. At the Artificial Intelligence Laboratory, research is conducted primarily in mechanisms, computer controls and vision. Some of the work performed at the laboratory has included tendon-activated hands and their control. This research has produced lighter, nimbler hands for a PUMA robot. Other research is directed on a "robot skin," which detects pressure to discriminate between similar objects and to determine part orientation. Robot vision research at the AI Laboratory includes real time processing and 3D vision. The Mechanical Engineering Department at MIT carries out research in computer-controlled teleoperators for undersea work, drive systems, vision and prosthetics.

Although the three universities mentioned above sponsor the largest robotics programs, there are many others also active in robotics R&D. In the following, we will list these universities with their focused areas of research and include wherever possible, the principal researchers, funding level and estimated staff.

New York University

Principal Researcher: Jack Schwartz
Funding: \$1.25 - \$1.5M per year from NAVSEA/ONR
Staff: 2 Faculties, 6-7 Graduate Students

- 0 Development of Special Purpose Robot Language
- 0 Software Algorithms: Obstacle Avoidance, Peg-in-Hole Assembly

Ohio State University

Principal Researcher: Robert McGhee
Funding: \$1M per year from NSF and DARPA

- 0 Leg Locomotion (Machine and Human)
- 0 Controls
- 0 Dynamics

Purdue University

Principal Researcher: L. Paul, B. Arash, S. Nof
Funding: \$100K per year from NSF

- 0 Vision
- 0 Programming Languages
- 0 Control Systems
- 0 Plant Modeling

Rensselaer Polytechnic Institute

Principal Researcher: Leo Hanifin, C. W. LeMaistre
Funding: Industrial Association, NSF

- 0 Computer Graphics Simulation of Robots and Layouts
- 0 CAM Controllers
- 0 Infrared, Sonar and Radar Sensors
- 0 Gripper Design
- 0 Robot Safety

University of Alabama

Principal Researcher: J. Hill, X. D. Zhang
Funding: \$0.5M to 0.75M per year from the Army
Staff: 5 - 6 Faculty, 6 - 12 Graduate Students

- 0 Manufacturing System Simulation
- 0 Stereoscopic Vision

University of Cincinnati

Principal Researcher: Ronald Huston
Staff: 4 Professionals

- 0 Robot Arm Design
- 0 Kinematics and Dynamics of Robots
- 0 Vision

University of Florida

Principal Researcher: Del Tesar
Staff: 10+ Faculty, 20 Graduate Students
Funding: Approximately \$1 Million (FY 82) from
DOE, NSF, Army and the State of Florida

- 0 Robot Arm and Actuator Design
- 0 Computer-Based Teleoperators
- 0 Kinematics and Dynamics of Robot
- 0 Locomotion in Battlefield Conditions
- 0 Hierarchical Controls Using Force Feedback

University of Maryland

Principal Researcher: Azriel Rosenfeld
Funding: \$1M+ per year

- 0 Vision and Image Interpretation
- 0 Real Time Programming Systems for Sensor and Control Interaction
- 0 Artificial Intelligence

University of Massachusetts

Principal Researcher: Kiuchi Masubuchi
Funding: \$300K from NSF. Additional Funding from
NAVSEA

- 0 Part Design for Automatic Assembly
- 0 Economic Application of Assembly Robots
- 0 Control of Welding Operations

University of Michigan

Principal Researcher: D. E. Atkins
Funding: \$500K from State of Michigan. Additional
Funding from Air Force, AFSC, AFOSR
Staff: 17 Faculty, 35 Graduate Students

- 0 One of AFOSR's "centers of excellence"

- 0 Programming Languages
- 0 Vision
- 0 Control Systems

University of Rhode Island

Principal Researcher: Robert Kelley
Funding: \$200K (FY 82) from NSF
\$1M (FY 82) from Industry

- 0 Vision Software
- 0 Dexterous Gripper Designs
- 0 Programming Languages
- 0 Manufacturing System Design

University of Rochester

Funding: \$200K from NSF and ONR

- 0 Vision
- 0 Computer Graphics Languages Called PADL for Storing 3D Shapes in Computer
- 0 Automation of Manufacturing

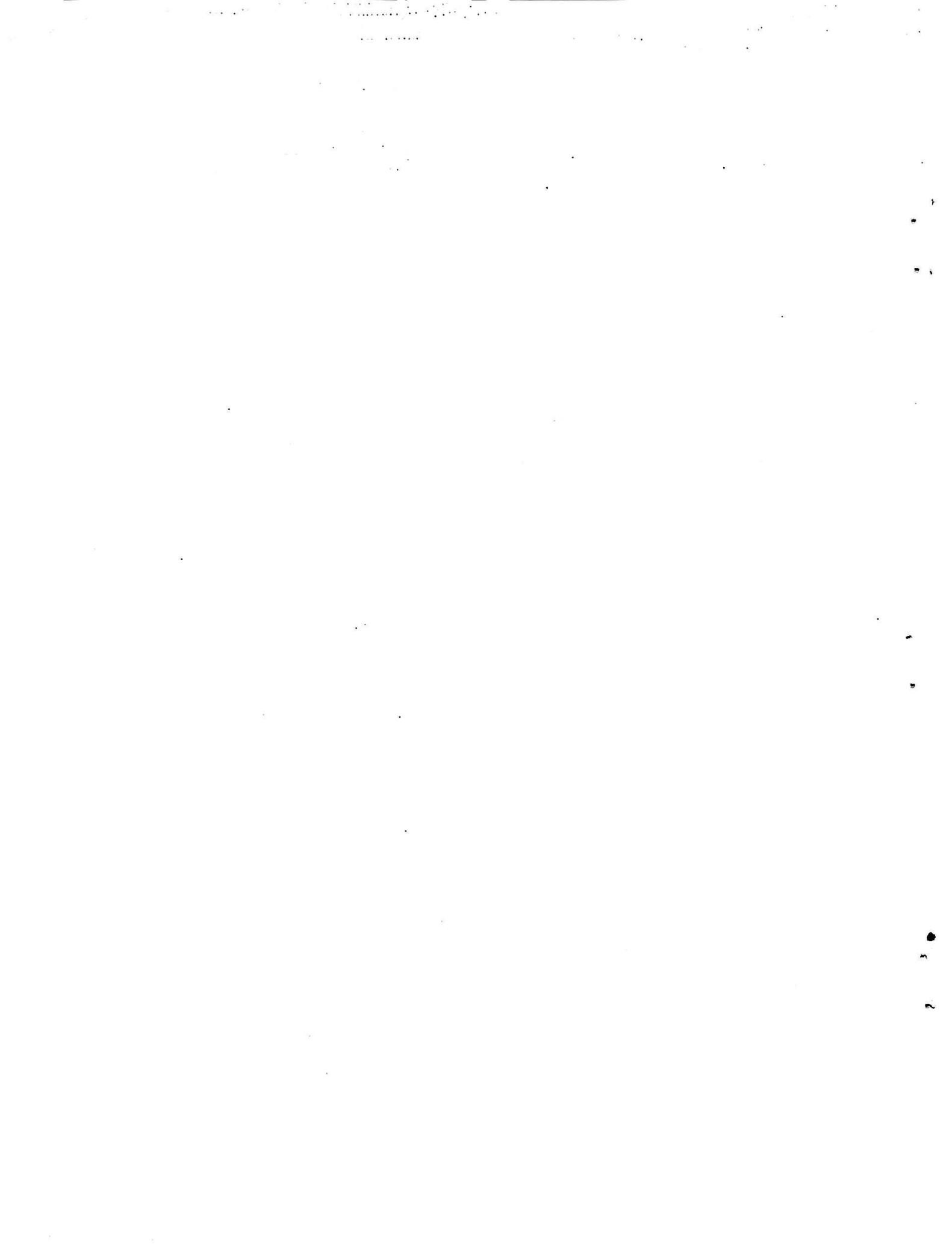
University of Tennessee

Principal Researcher: Dr. Gonzales
Funding: \$0.5 to 0.75M/Yr from NSF
Staff: 3 Faculty, 20 Graduate Students

- 0 Integrated Sensory Research

In addition, there are a number of universities that have participated in robotics research to a lesser extent. For completeness, they are listed as follows:

Case Western Reserve University, Clemson University, Duke University, George Washington University, Georgia Institute of Technology, Illinois Institute of Technology, Lehigh University, Louisiana State University, North Carolina State University, Northwestern University, Oregon State University, Rice University, Texas A&M, University of Arizona, University of Central Florida, University of Connecticut, University of Illinois at Chicago, University of Minnesota, University of New Mexico, University of Pennsylvania, University of Southern California, University of Tennessee, University of Texas, University of Virginia, University of Utah, University of Washington, University of Wisconsin, and Virginia Polytechnic Institute.



Appendix D

Bibliography

1. Proceedings

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5. Control

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8. Personal Communications

Following is the list of information sources that were collected during the course of study through a number of personal contacts in various forms. These references are cited here according to the following format:

Name, Information Content, Form of Communication, Date

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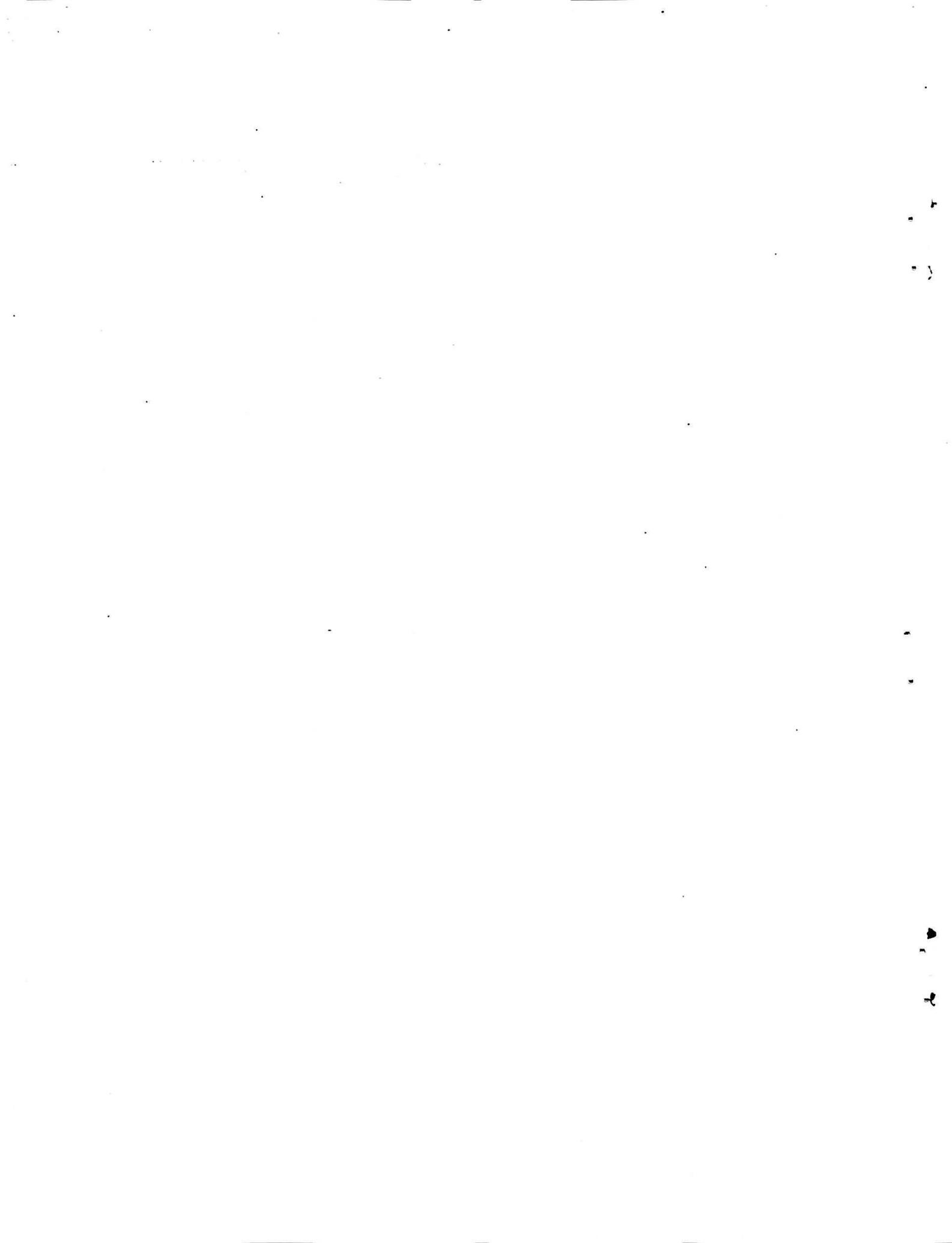
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Brasseau, G., Summary of NSF-sponsored projects on robotics, February 1984.



APPENDIX E

List of Contacts

During the course of this study, DHR approached many agencies and individuals to obtain information about their involvement in the robotic field. Our interaction with them took place in various forms such as telephone interviews, personal meetings or written communications. Below is a list of these individuals and their affiliations. Due to the limited space, we are obliged to neglect a number of contacts which are also very helpful but of a lesser significance.

1. Air Force

USAF Headquarters
Fiorino, Col. Tom
Room 4C283, Pentagon
Washington, D.C. 20330
202/697-1417

Air Force Office of Scientific Research
Electronic and Material Sciences
Windsor, LtC.
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Bolling AFB, Washington, D.C.

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AFHRL/X
McCall, Maj.
Brooks AFB, TX 78235
512/536-3853

Aerospace Medical Division
AFSC/AMD/RDX
Beatty, Col. Dave
Brooks AFB, TX 78235
512/536-3406

Contract Management Division
AFSC/AFCMD/PD
Glover, Vern
Kirtland AFB, NM 87117
505/844-9656

Air Force Flight Test Center
AFSC/AFFTC/XRX
Johnston, Robert
Edwards AFB, CA 93523
805/277-3837

Air Force Geographics Laboratory
AFSC/AFGL/XOP
Posiadjo, Ron
Hanscom AFB, MA 01730
617/861-3606

Air Force Weapons Laboratory
AFSC/AFWL/PRP
Algermission, Robert
Kirtland AFB, NM 87117
505/844-9376

Arnold Engineering Development Center
AFSC/AEDC/DEM
Hartig, Maj.
Arnold AFS, TN 37389
615/455-2724

Ballistic Missile Office
AFSC/BMO/PMD
Roundtree, Maj. W.J.
Norton AFB, CA 92409
714/382-6014

Space and Missile Test Organization
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805/866-1662

Air Force Logistics Command Headquarters
AFLC/MAXT
Hary, Lazlo
Wright Patterson AFB, OH 45433
513/257-7114

Air Force Logistics Command Headquarters
AFLC/MAXE
Head, Lawrence J.
Wright Patterson AFB, OH 45433
513/257-6163

Aerospace Medical Division
AFSC/AMD/RDT
Herrah, Col.
Brooks AFB, TX 78235
512/536-2091

Air Force Materials Laboratory
AFSC/ASD/AFWAL
Lee, Sylvester
Wright Patterson AFB, OH 45433
513/255-5151

Space Division
AFSC/SD/PDP
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Los Angeles AFS, CA 90009
213/643-0854

Manufacturing Technology Division
AFSC/ASD/ARWAL/MLTC
Schultz, William

Air Force Materials Laboratory
AFSC/ASD/AFWAL
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Wright Patterson AFB, OH 45433
513/255-2738

Manufacturing Technology Division
AFSC/ASD/AFWAL/MLTC
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Griswold, Roger
Wright Patterson AFB, OH 45433
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2. Navy, Army and DARPA

Naval Air Systems Command
Warren, Robert
Washington, D.C. 20350
202/692-2515

Naval Air Systems Command
Aircraft Division
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JP-1
Washington, D.C. 20350
202/692-7443

Naval Sea Systems Command
SEA-90M
Everett, LCDR Hobart
Washington, D.C. 20362
202/692-6465

NAVSEA/David Taylor Naval Ship Div.
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Carderock, MD
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Naval Surface Weapons Center
Werneth, Russell
Silver Spring, MD 20910
202/394-3256

Naval Ocean Systems Center/NOSC
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San Diego, CA 92152
619/225-2083

Office of Naval Research
Information Sciences Program
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DARPA
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1400 Wilson Blvd.
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DARCOM/DRCMT
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50001 Eisenhower Ave.
Alexandria, VA 22333

DARCOM
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309/794-3682

Human Engineering Laboratory/Army Proving Ground
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3. NSF, NASA, NBS, Dept. of Commerce.

NASA HQ/Computer Science and Automation
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Automated Manufacturing Research Facility
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301/921-2181

Dept. of Commerce
Kravalis, Hedija
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Washington D.C. 20230
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4. Industry

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Hartman, Dale
Woodtli, Ernest
Krag, Neils
Harger, Robert A.
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McMahon, Steve
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Chicago, IL 60603
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Cincinnati Milacron
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Lebanon, OH 45036
513/932-4400

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Developmental Manufacturing
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206/655-4550

GCA Corp.
Industrial Systems Group
Kirkpatrick, Lane
Naperville, IL 60566
312/369-2110

H.E. Buffum Co.
Buffam, Harvey
Anacortes, WA 98221
206/725-5040

Ceeris International, Inc.
D'Agostino, Salvatore
Old Lyme, CT 06371
203/434-8740

LTV Aerospace and Defense Company
Vought Aero Products Division
Gandhi, Chander
Dallas, TX 75265
214/266-2680

5. University

University of Massachusetts
Arbib, Michael
Amherst, MA
413/545-2743

George Washington University
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202/676-6083

Massachusetts Institute of Technology
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University of Texas, Austin
Busch-Vishniac, Ilene
Austin, TX 78172
512/471-3038

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Baton Rouge, LA 70803
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University, AL 35486
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University of Rhode Island
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Robotics Research Center
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Johns Hopkins University
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212/460-7209

North Carolina State University
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